JPL Advanced Thermal Control Technology Roadmap

a presentation to

Spacecraft Thermal Control Workshop
The Aerospace Corporation, El Segundo California
March 25, 2019

Eric Sunada / Jose Rodriguez
NASA Jet Propulsion Laboratory
California Institute of Technology

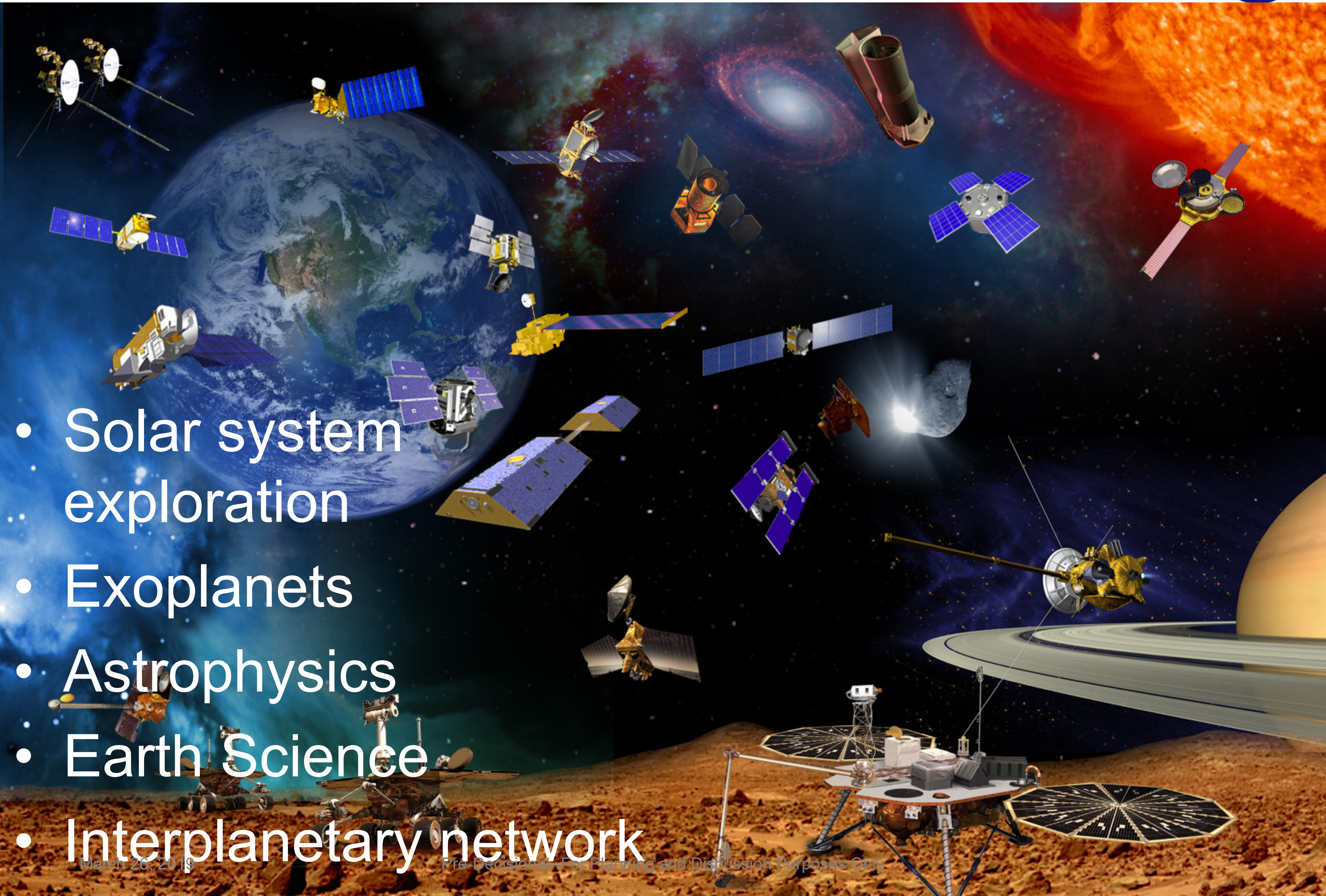
Jet Propulsion Laboratory
California Institute of Technology

JPL CL#19-1669

Introduction to NASA JPL

- Federally (NASA)-owned “Federally-Funded Research and Development Center” (FFRDC)
- University (Caltech)-operated
- 6,000+ employees (mostly Caltech)
- 100+ acres

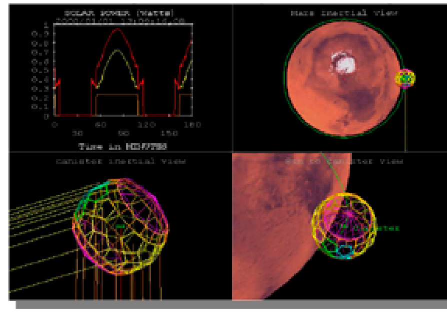
JPL's focus is robotic space exploration



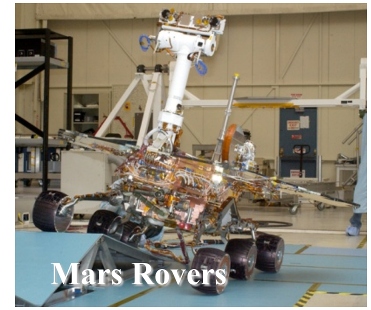
- Solar system exploration
- Exoplanets
- Astrophysics
- Earth Science
- Interplanetary network

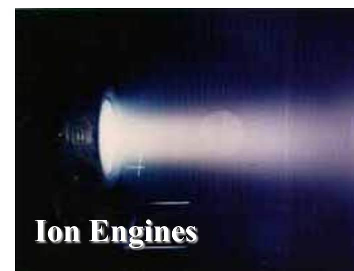
End-to-end capabilities

Project Formulation - Team X

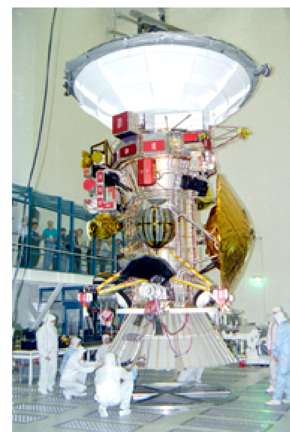


Mission Design

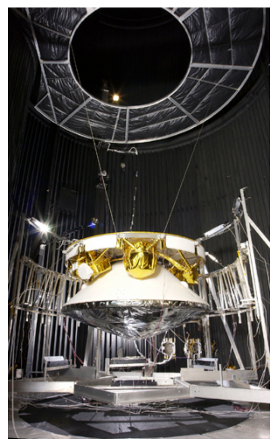




Spacecraft Development



Integration and Test



Environmental Test

Real Time Operations

Outline

- Current and proposed flight projects
  - Status from the thermal subsystem perspective
- Thermal technology challenges and roadmap

Current and proposed projects

Status from the thermal subsystem perspective

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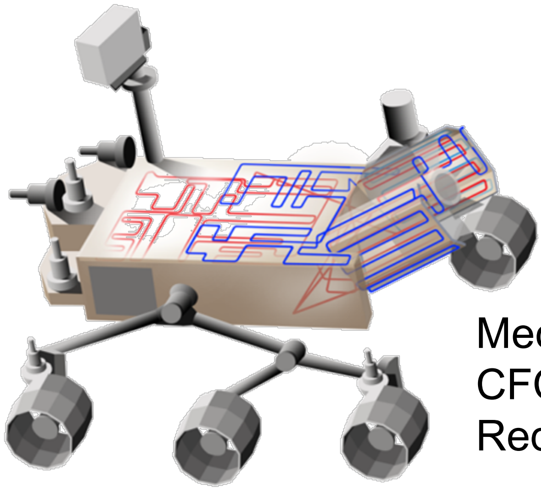
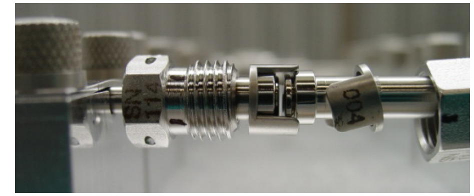
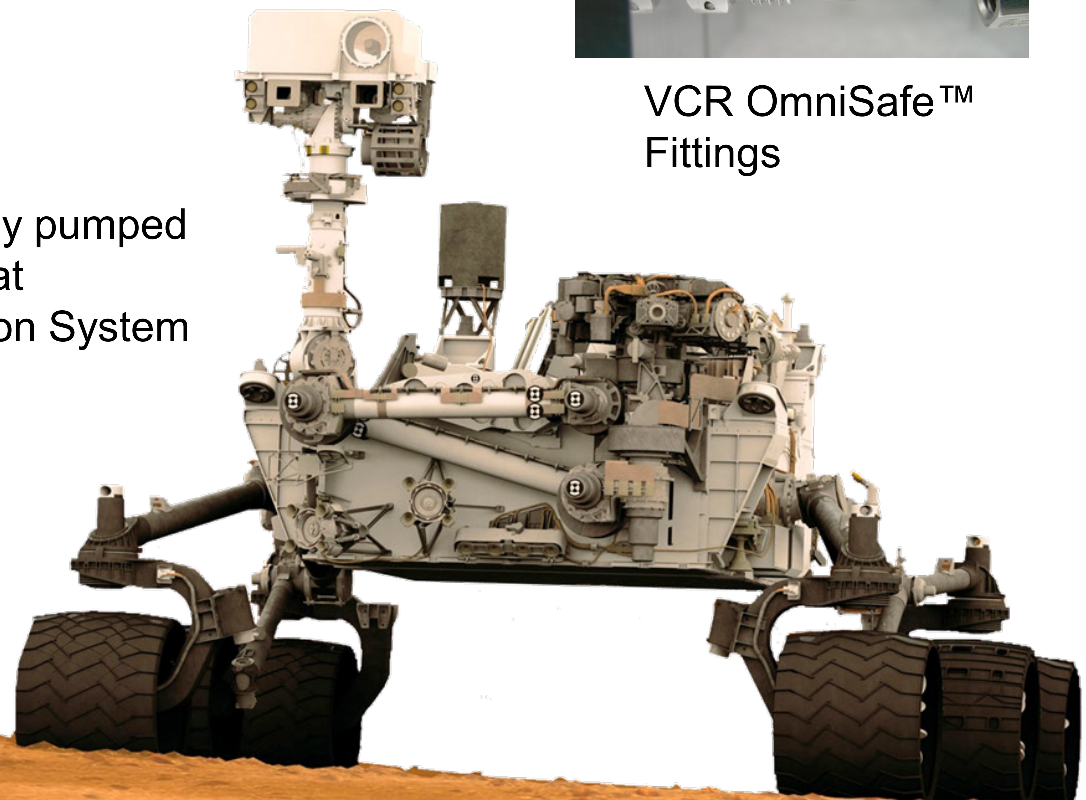
Curiosity Rover on Mars



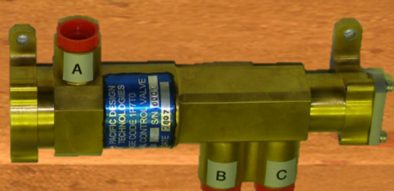
Mechanically pumped CFC-11 Heat Redistribution System



VCR OmniSafe™ Fittings



Centrifugal Pump (PDT, Inc.)

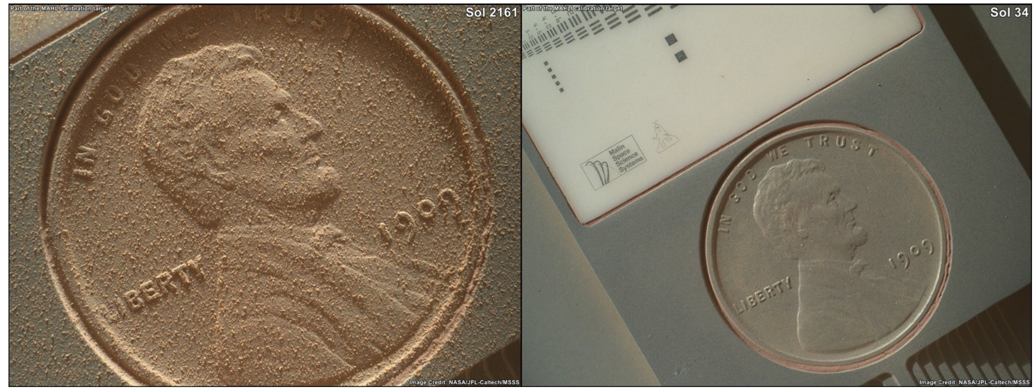


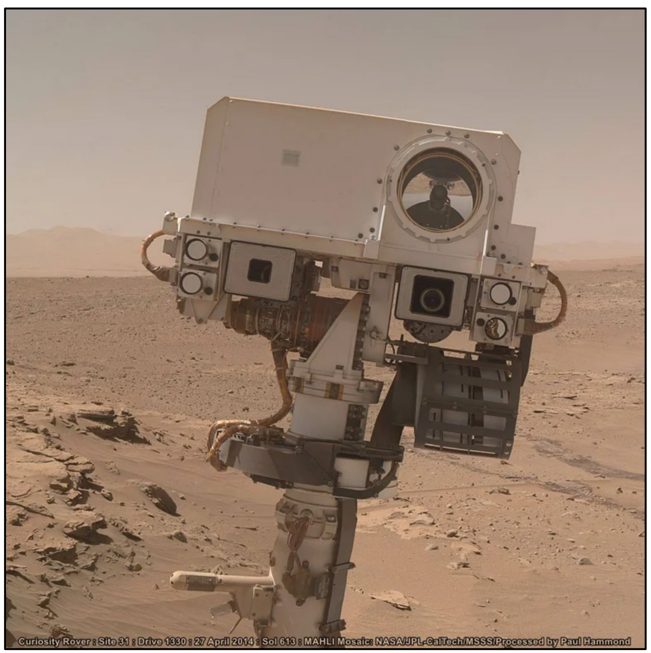
Passive Thermal Control Valves, splitter and mixer (PDT, Inc.)

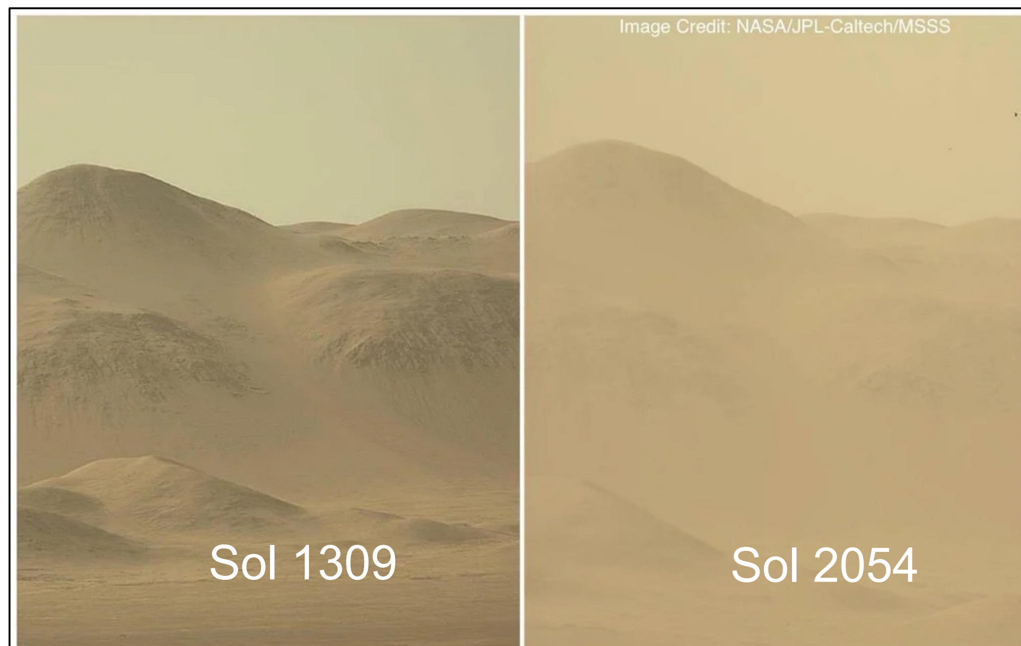
Curiosity Rover—Thermal Status

(Courtesy of Kurt Gonter, Curiosity Rover Thermal Operations Engineer)

- Total odometry: 20,486m
- RTG output nominal at ~86-89 W_e
- Global dust storm had pronounced thermal effects
  - Diurnal temperature swings reduced from **70C to 30C**
  - Approximately 100 sols until thermal environment returned to pre-storm levels



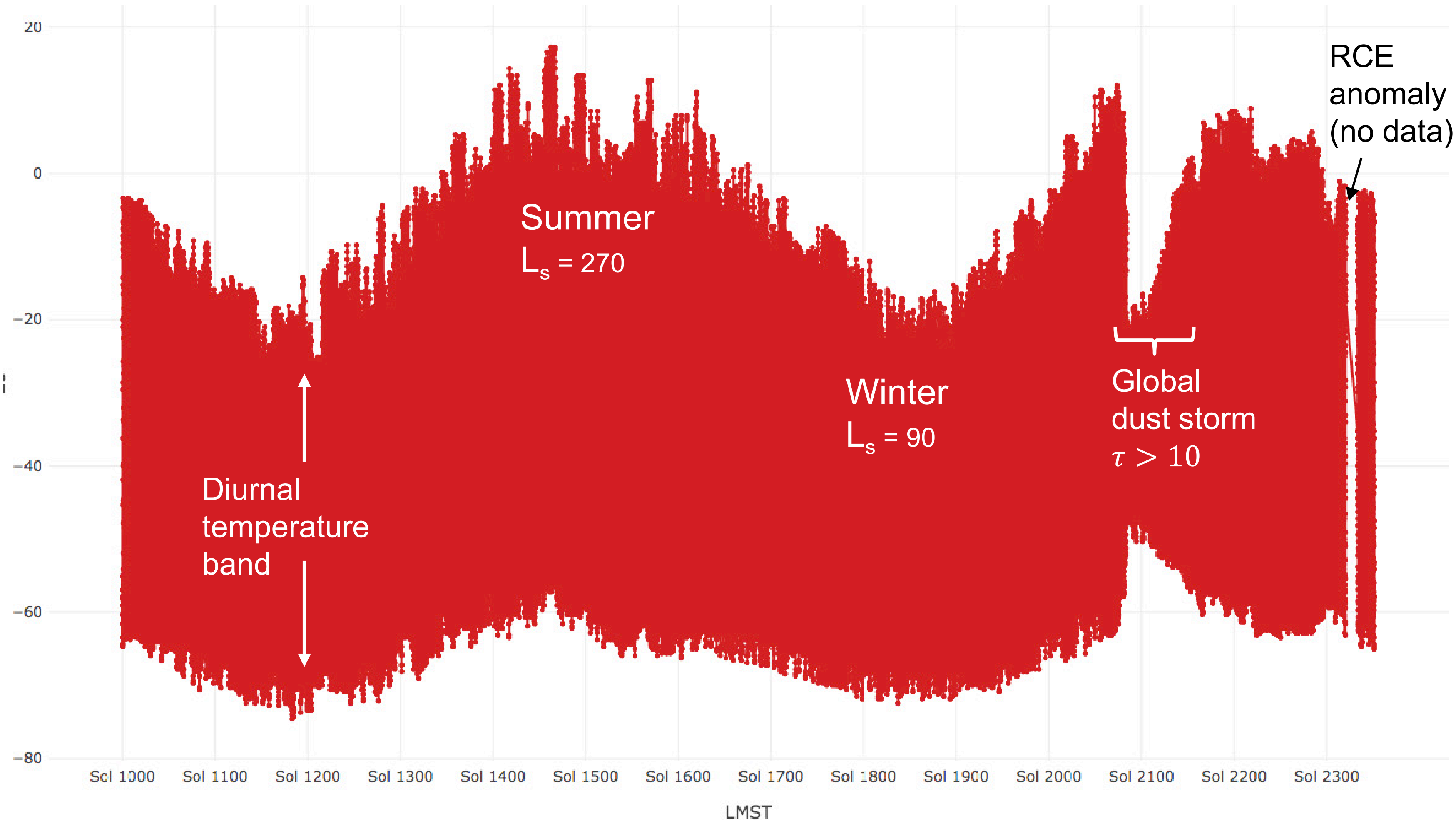




Curiosity Rover—Thermal Status

(Courtesy of Kurt Gonter, Curiosity Rover Thermal Operations Engineer)

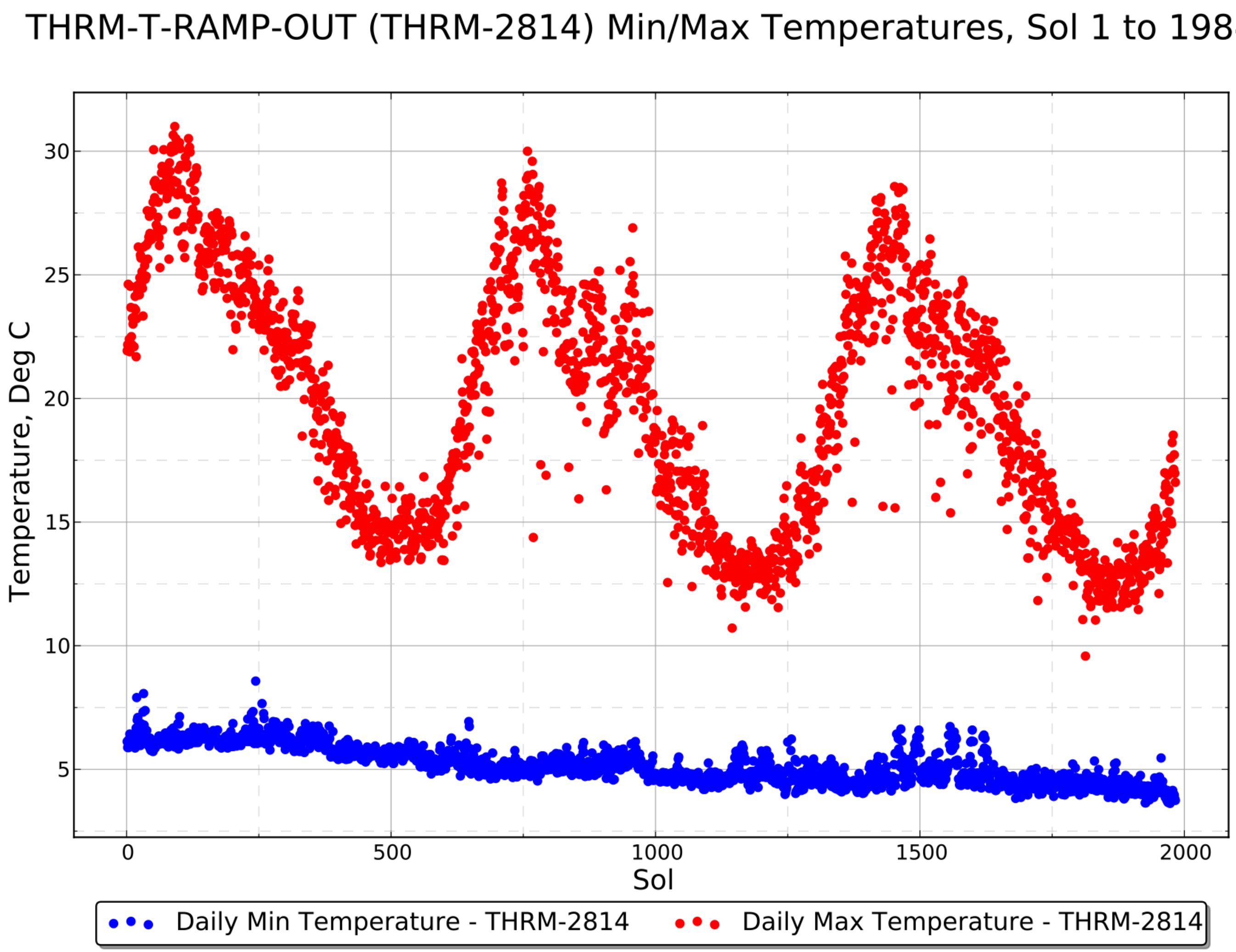
Robotic Arm (RA) Shoulder Mounting Bracket Temperatures



Curiosity Rover—Thermal Status

(Courtesy of Gordon Cucullu, Thermal/Fluid Systems & Mission Operations Group Supervisor)

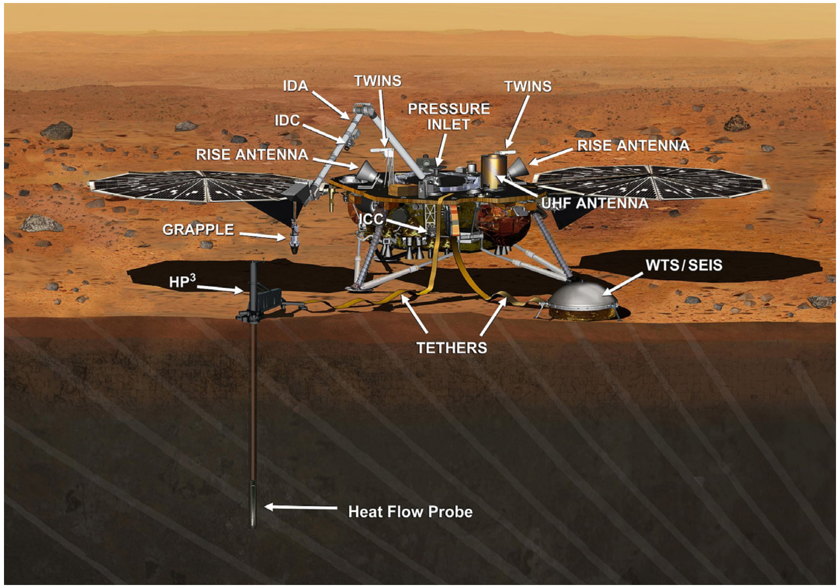
Rover Avionics Mounting Panel (RAMP) Temperatures



Mars InSight Lander
(May 5, 2018 Launch—Nov 26, 2018 Landing)

Science Goals and Objectives:

- Understand the formation and evolution of terrestrial planets through investigation of the interior structure and processes of Mars by
  - Determining the size, composition and physical state(liquid/solid) of the core.
  - Determining the thickness and structure of the crust.
  - Determining the composition and structure of the mantle.
  - Determining the thermal state of the interior.
- LM responsible for spacecraft, integration, test, launch operations and mission operations support. CNES providing SEIS, and DLR providing HP3 . Centro de Astrobiología (CAB) of Spain providing wind and air temperature sensors.
- JPL manages the mission for NASA



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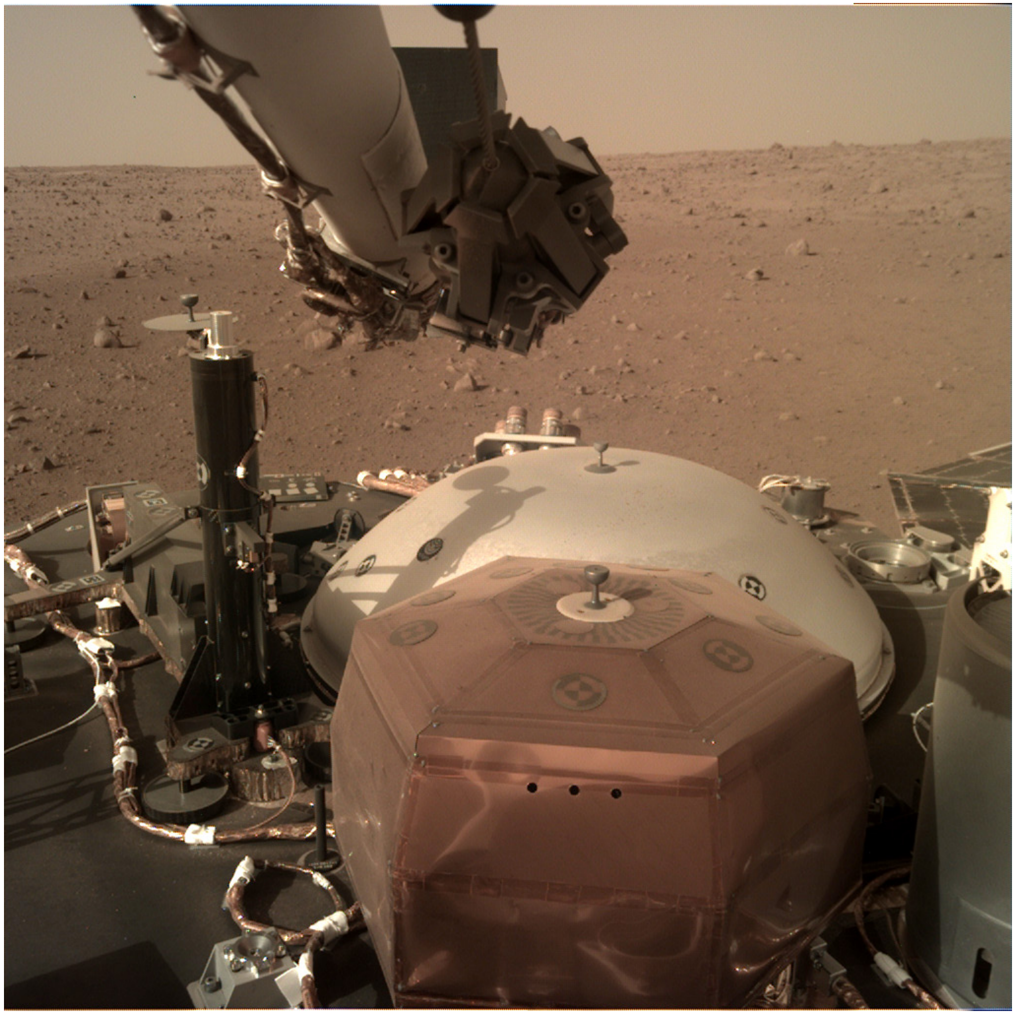
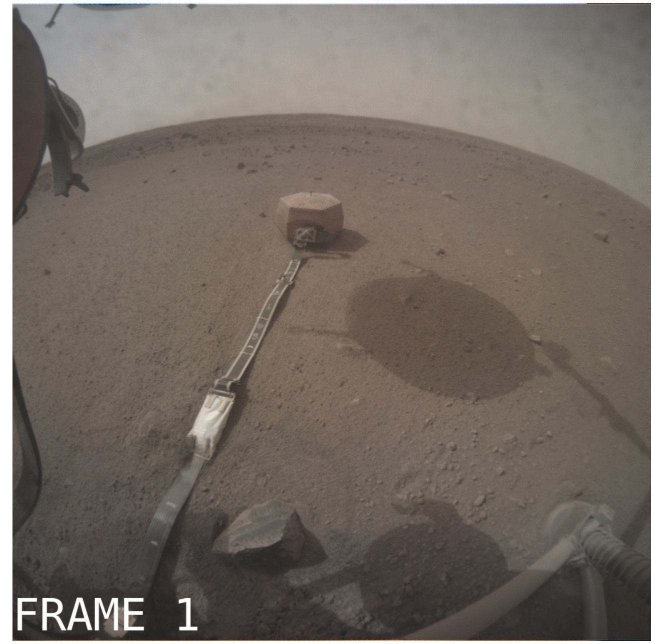
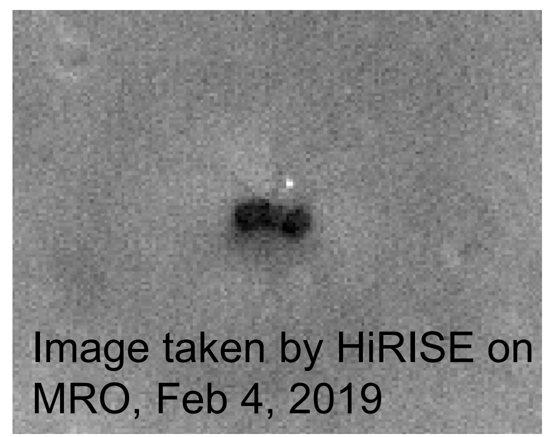




SEIS Instrument Deployed on Mars



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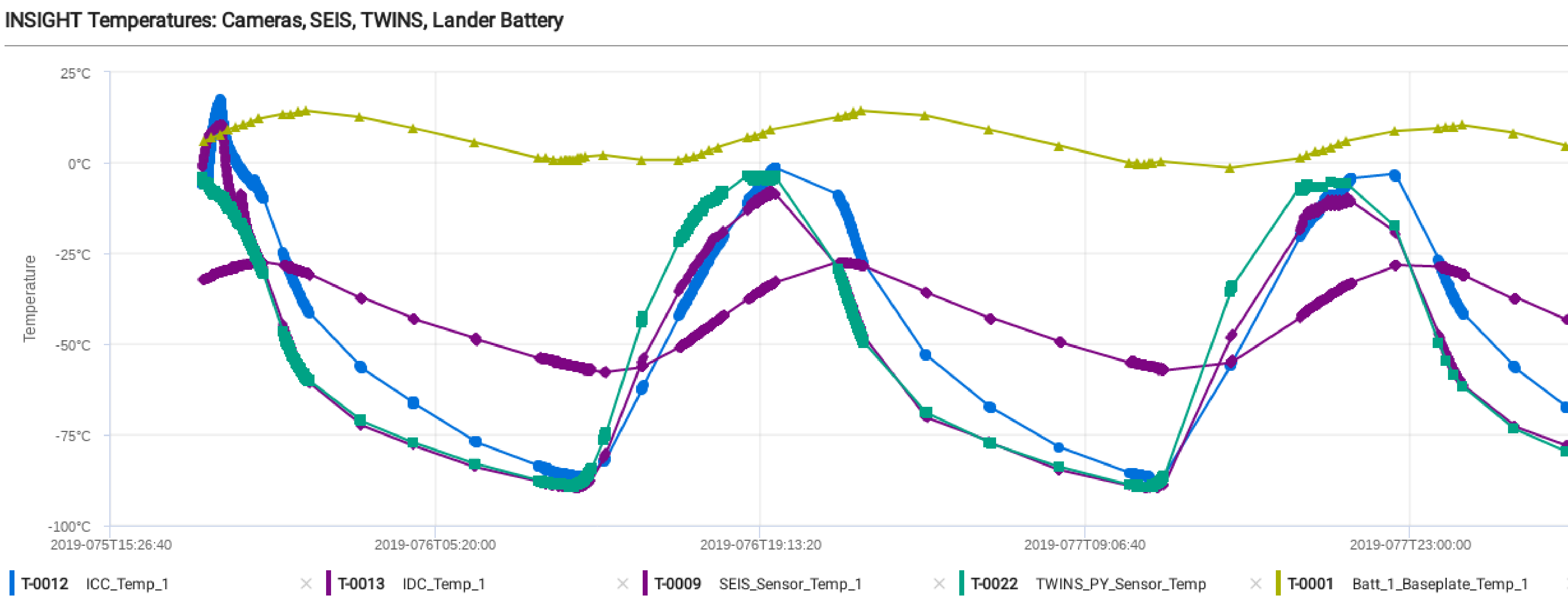
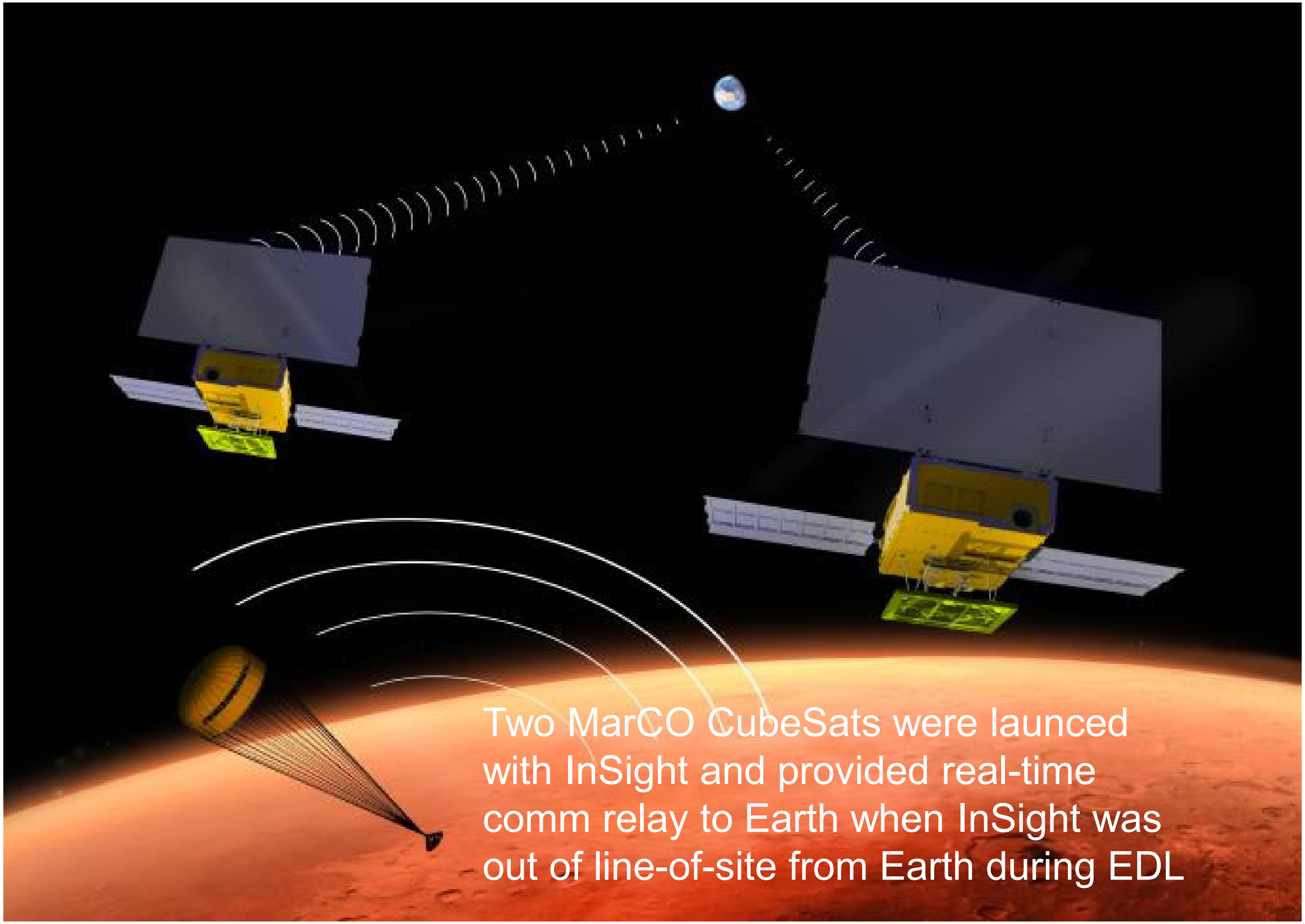


Mars CubeSat Orbiter (MarCO)

(Courtesy of Daniel Forgette, MarCO Thermal Lead)



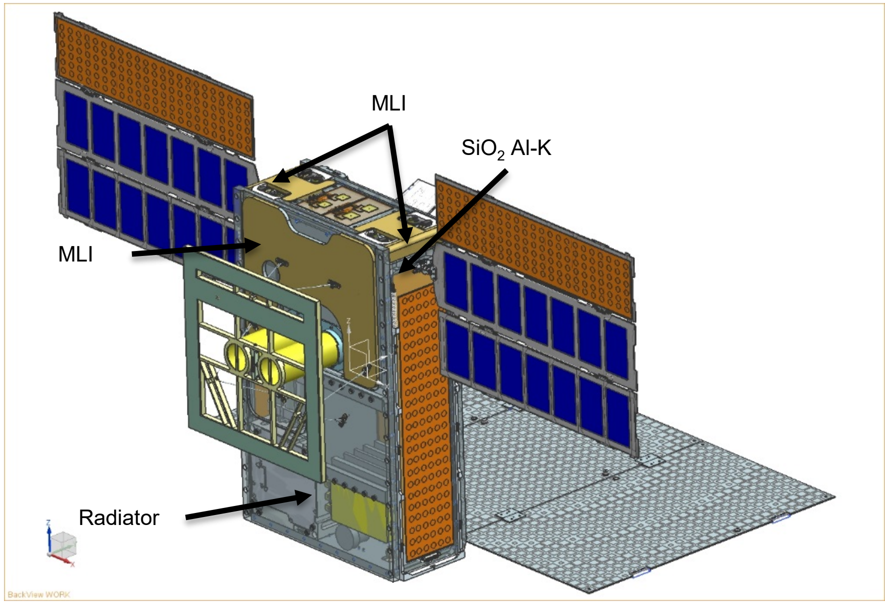
Mars CubeSat Orbiter (MarCO)

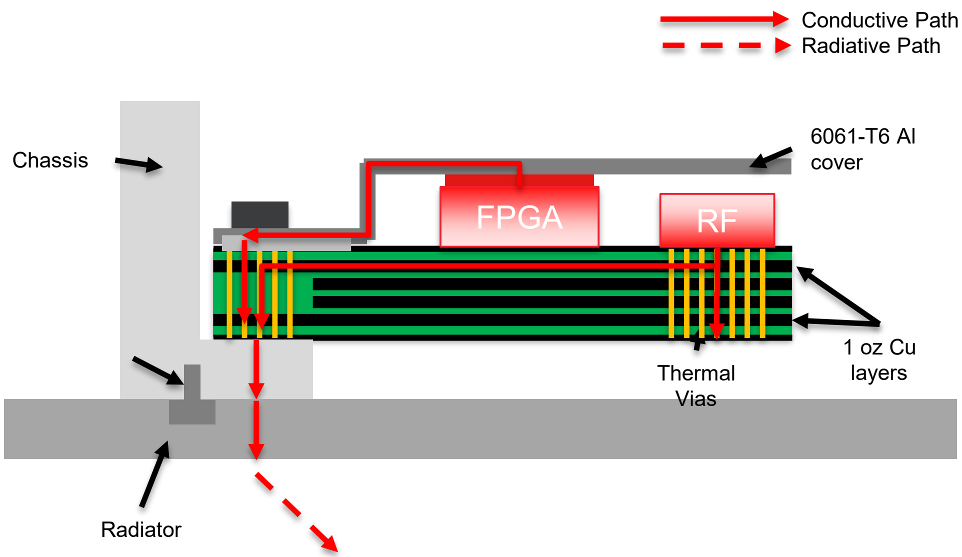
(Courtesy of Daniel Forgette, MarCO Thermal Lead)

Spacecraft delivered to

Thermal Subsystem

- Transponder with high power density
  - Dedicated thermal PWB Cu layers
  - Custom Al thermal cover for FPGA
  - High conductance chassis
- Radiator sized for S.S. -10°C operation at 15 W
- Capability for ~ 3 hours transmit time





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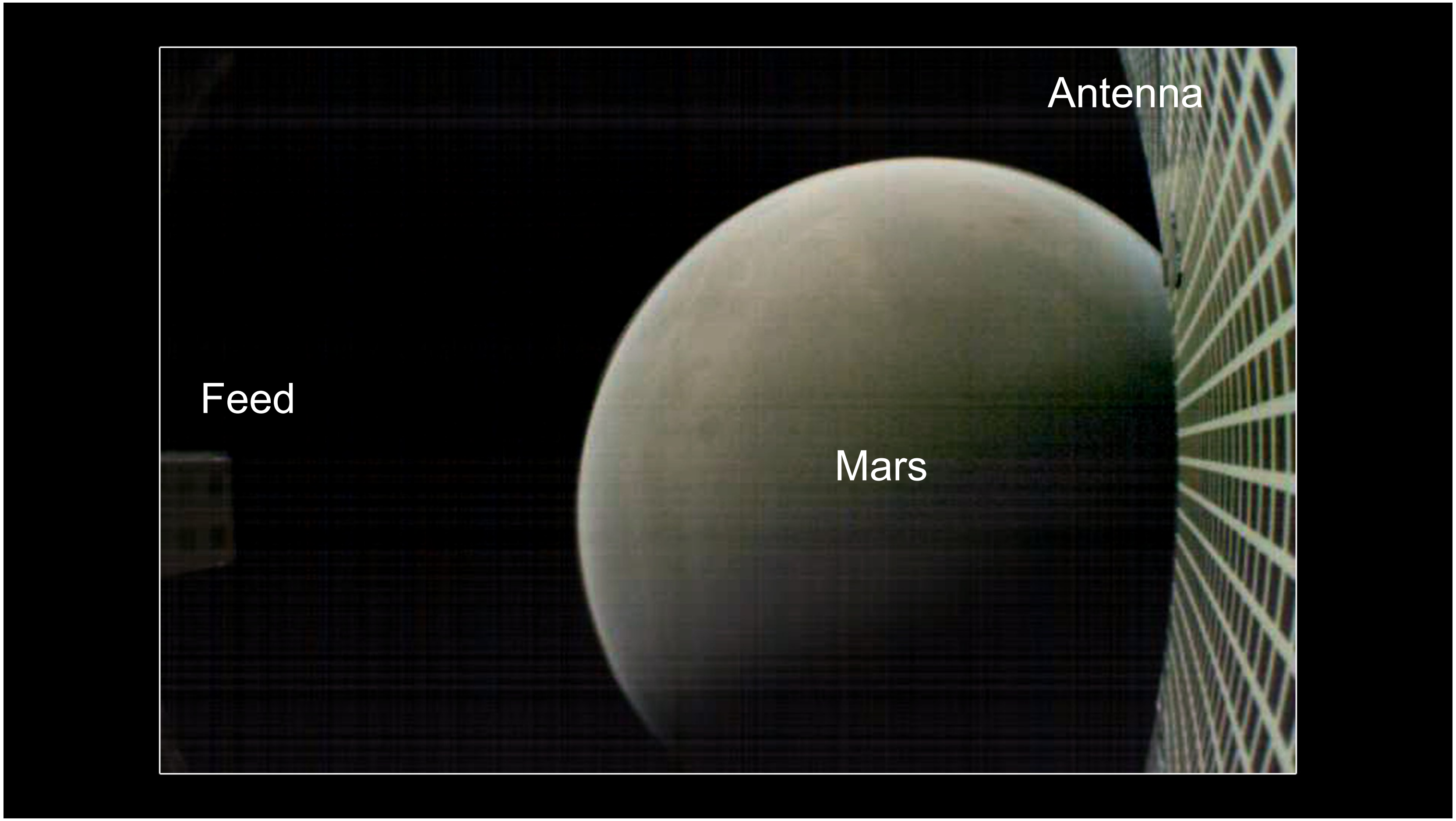
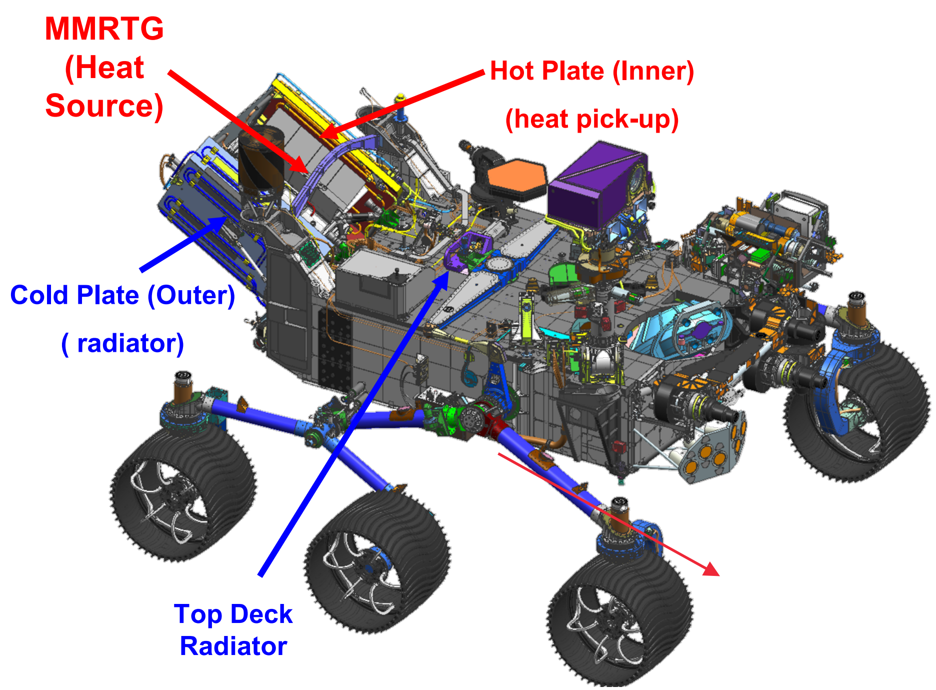


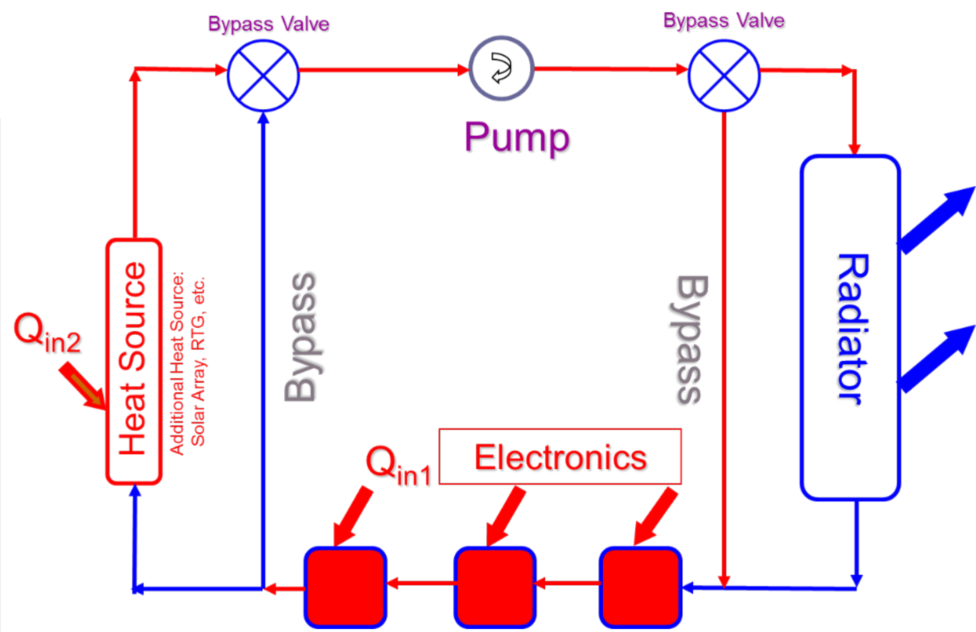
Image taken by MarCO-B, Nov 26, 2018

Mars 2020 Rover

(Courtesy of Jason Kempenaar, M2020 Surface Thermal Lead)

- Key functions of M2020 Rover Heat Redistribution System (RHRS):
  - Removal of waste heat from rover during Cruise phase of mission
  - Removal of waste heat from rover and MMRTG during hot part of the day
  - Recovery of waste heat from MMRTG during the cold part of the day for internal heating
  - Thermally couple RAMP masses for increased thermal capacitance to reduce amplitude of temperature swings
- RHRS fluid tubes are embedded in RAMP to remove or add heat to keep the science and engineering hardware at safe operating and survival temperatures

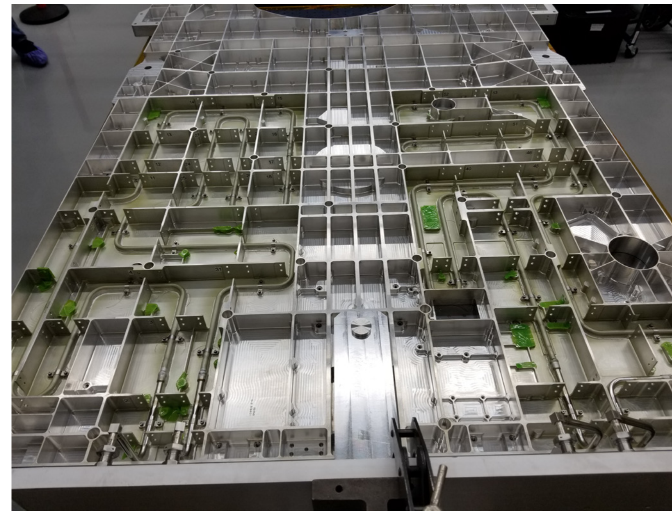




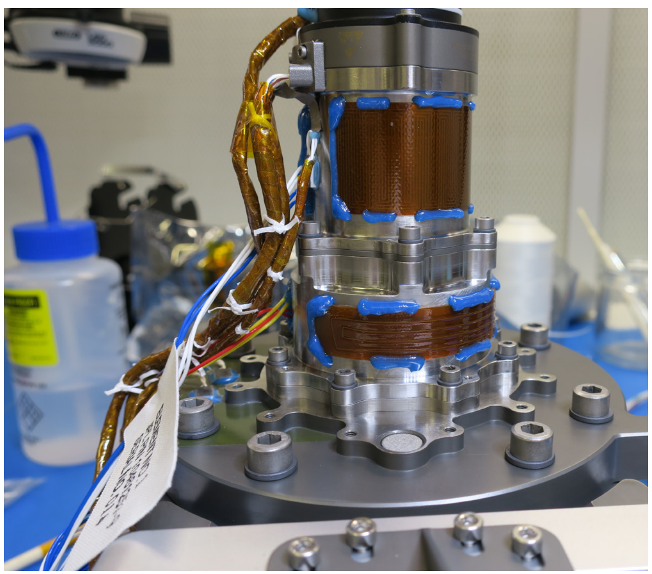
Pumped Fluid Loop Based Thermal *Bus* Architecture
(*Supply* *as well* as *Reject* Heat)

Mars 2020 Rover Hardware

- Spacecraft-level System Thermal Test, April 2019
- Launch: July 17, 2020



Top Deck HRS Tubing being bonded

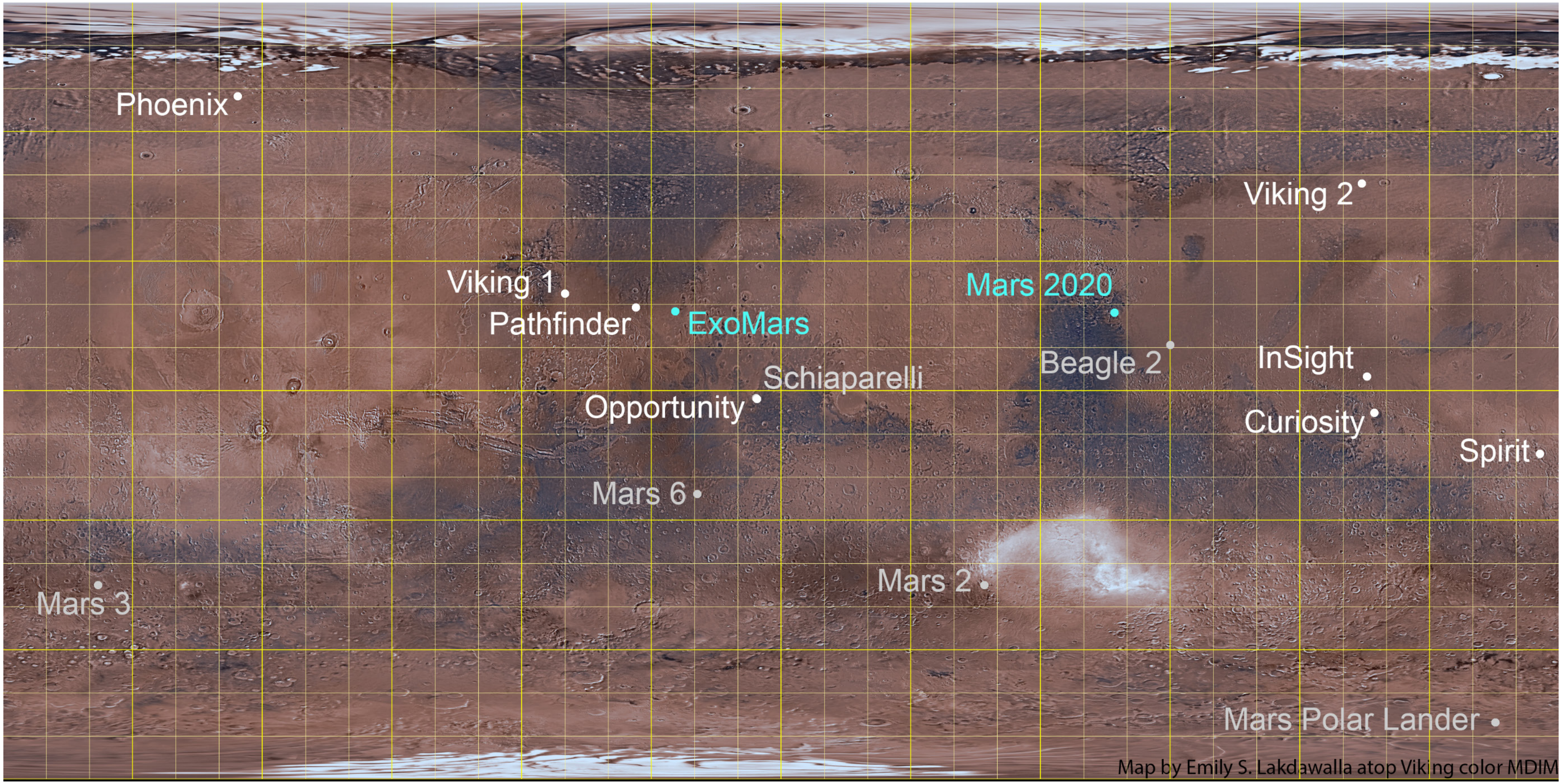


Heater Installation on Robotic Arm Actuators

MMRTG HX Tubes

Mars 2020 Rover Landing Site

- Landing: Feb 18, 2021 at Jezero Crater, 19° N

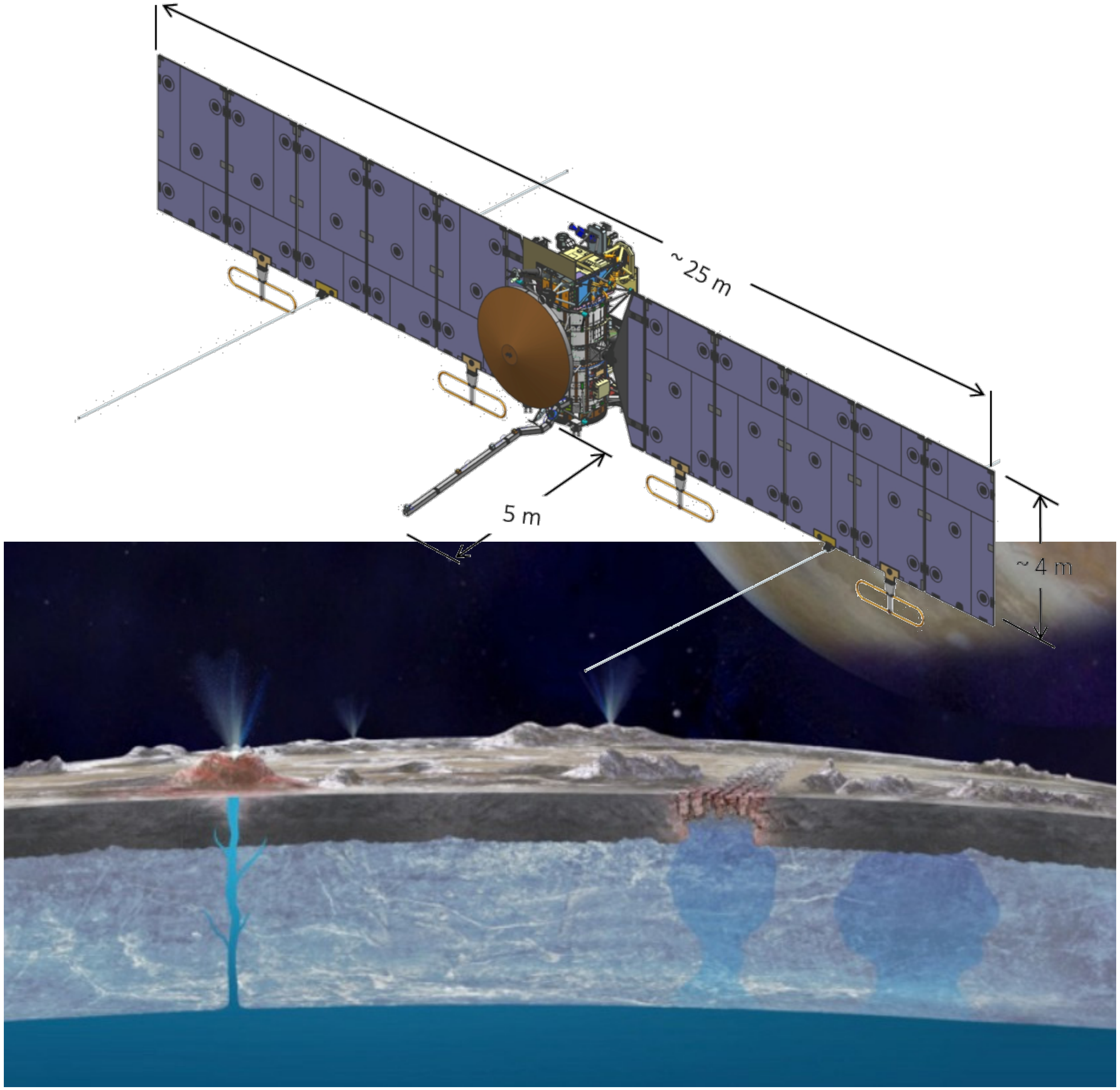


Credit: NASA / JPL / USGS (image); Emily Lakdawalla (map)

Europa Clipper Mission

(Courtesy of Dr. Tony Paris, JPL Europa Thermal Subsystem Lead)

- From Jupiter orbit, perform a detailed investigation of the giant planet's moon Europa -- a world that shows strong evidence for an ocean of liquid water beneath its icy crust and which could host conditions favorable for life.
- Constraints for the spacecraft design include limited electrical power for heating, long mission lifetime, and tolerance for high radiation environments.



Planned Europa Clipper Mission

(Courtesy of Dr. Tony Paris, JPL Europa Thermal Subsystem Lead)

- Thermal architecture
  - Single-phase, mechanically pumped fluid loop
  - Redistributes waste heat
  - System is being developed and tested for survivability in the Jovian environment

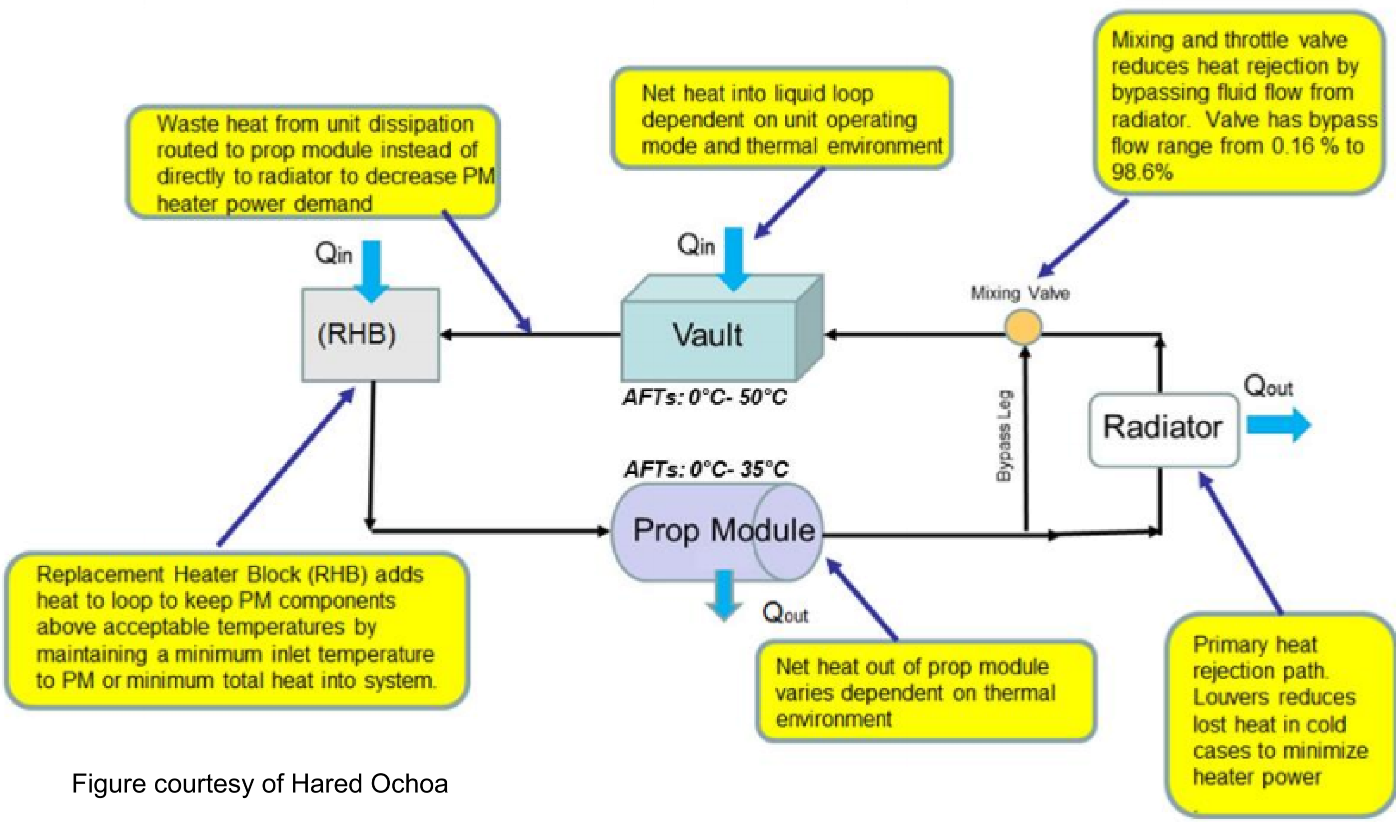
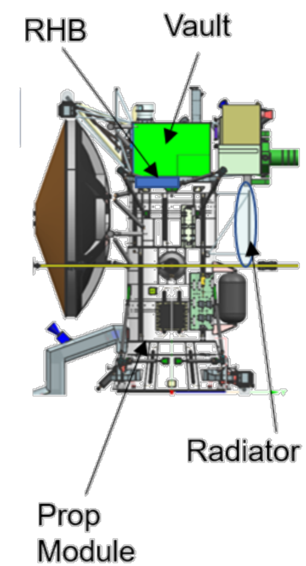


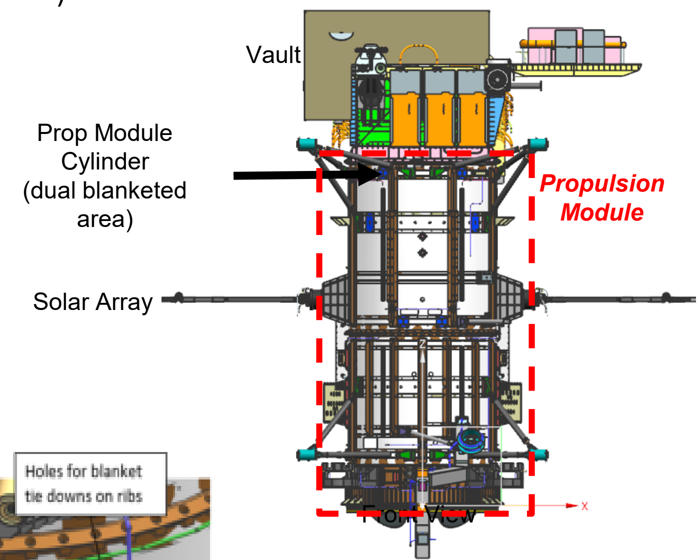
Figure courtesy of Hared Ochoa



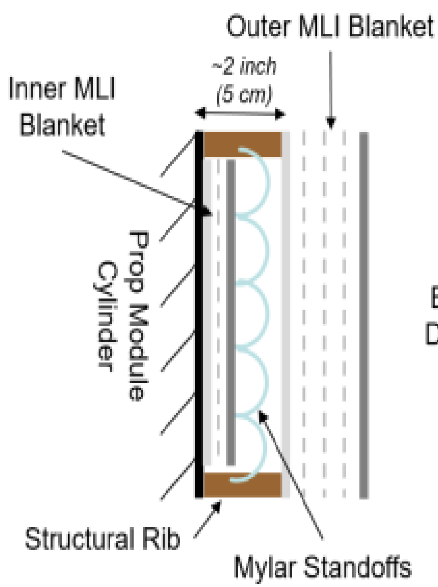
Planned Europa Clipper Mission

(Courtesy of Pradeep Bhandari, JPL Europa Thermal Chief Engineer)

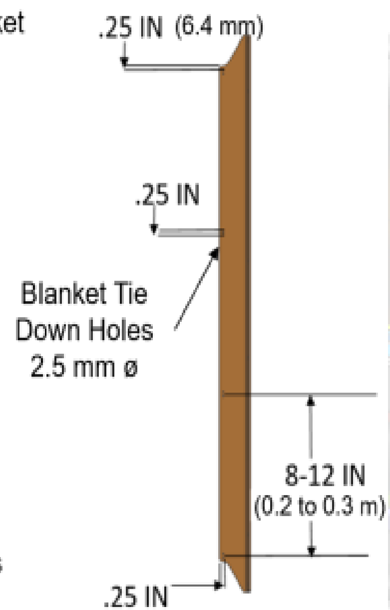
- Large propulsion module with a cylinder that is maintained between 0 and +35 °C
- Dual blanket MLI concept estimated to save ~ 80 W compared to a single blanket design



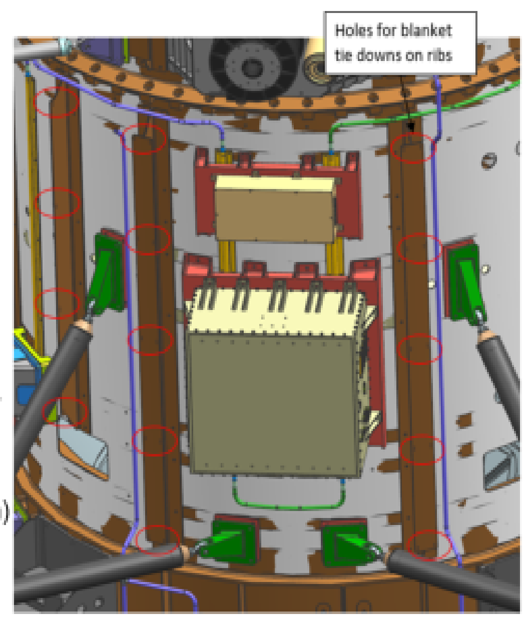
HGA and part of solar array hidden



Blanketing Schematic



Structural Rib and Blanket Tie Down Scheme

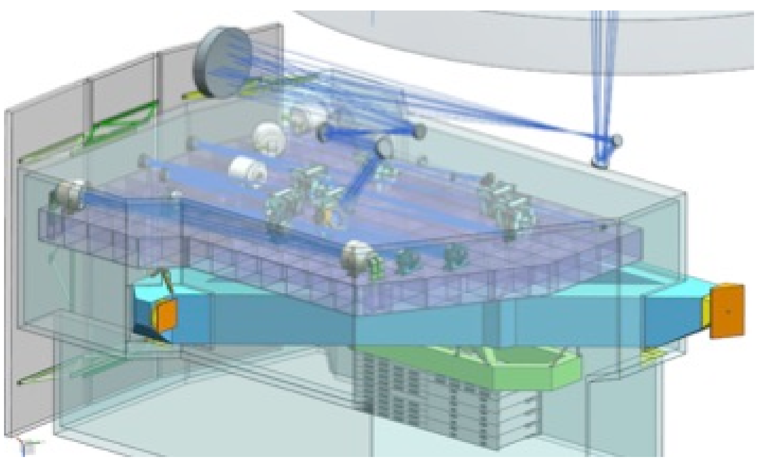


CAD Snapshot of Prop Module

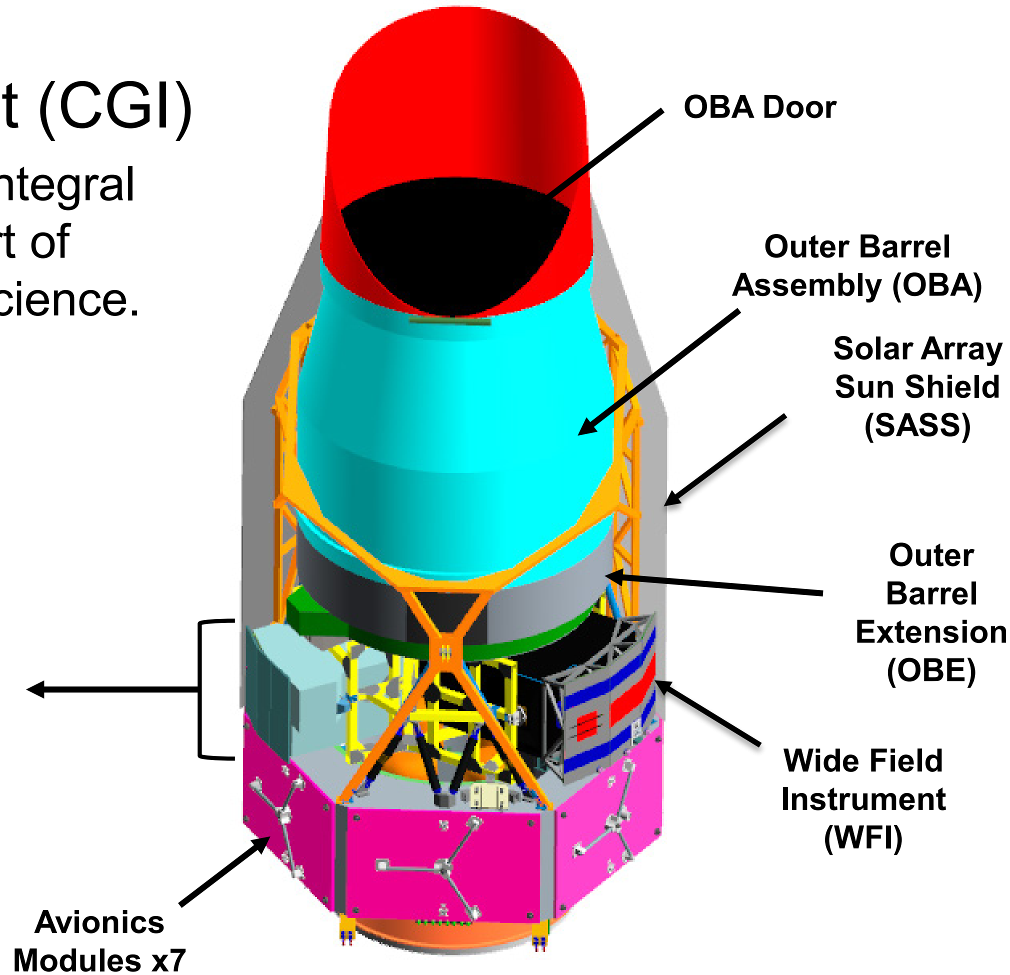
WFIRST/AFTA Exo-Planet Finder

(Courtesy of Gary Kuan, JPL WFIRST/AFTA Systems Engineer & Hung Pham, JPL Thermal Engineer)

- JPL is providing the Coronagraph Instrument (CGI)
  - High contrast imaging and integral field spectroscopy in support of exoplanet and debris disk science.



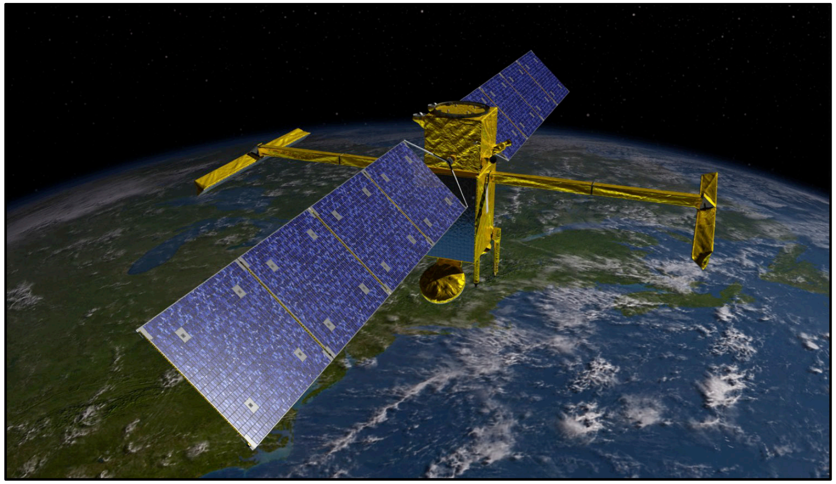
Coronagraph Instrument (CGI)

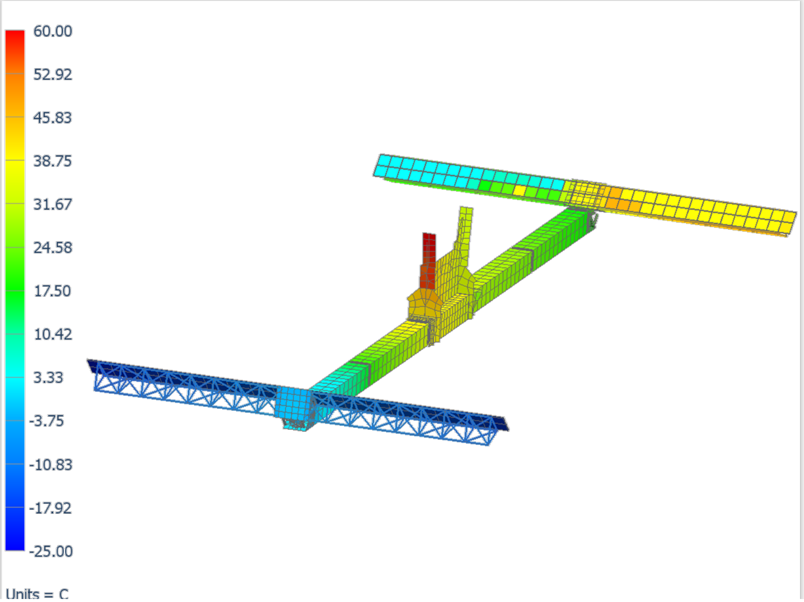


Surface Water Ocean Topography Mission

(Courtesy of Ruwan Somawardhana, JPL SWOT Thermal Lead)

- SWOT's mission objective is to characterize ocean topography to a spatial resolution as low as 15 km and provide a global inventory of surface water
  - Joint partnership between NASA and CNES
- Challenging combination of thermal requirements
  - Co-location requirements
  - >1000 W peak thermal dissipation
    - Heat fluxes as high as ~75 kW/m^2
  - Stability requirements as low as 0.05°C/min
- Thermal control subsystem utilizes four LHPs + CCHPs and AlBeMet doublers
- Project Status:
  - Testing at assembly-level and integration into instrument-level





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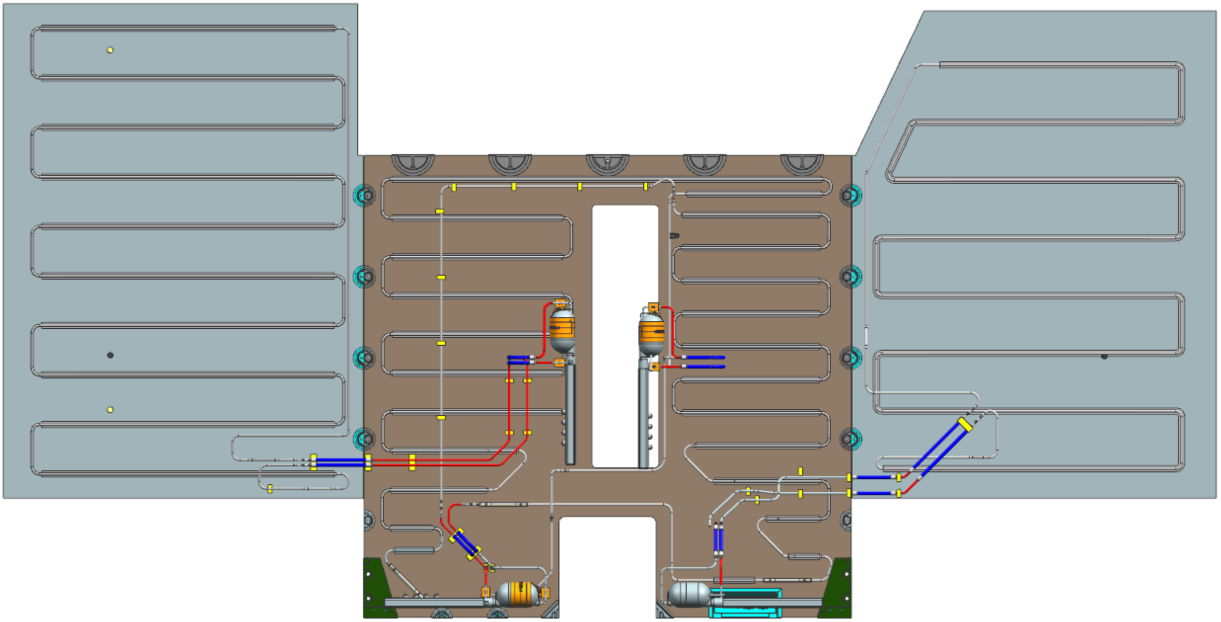
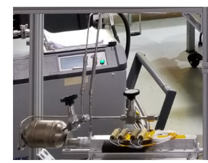


Flight LHP Assembly



VDA/White Paint Striping on Composite Qualification

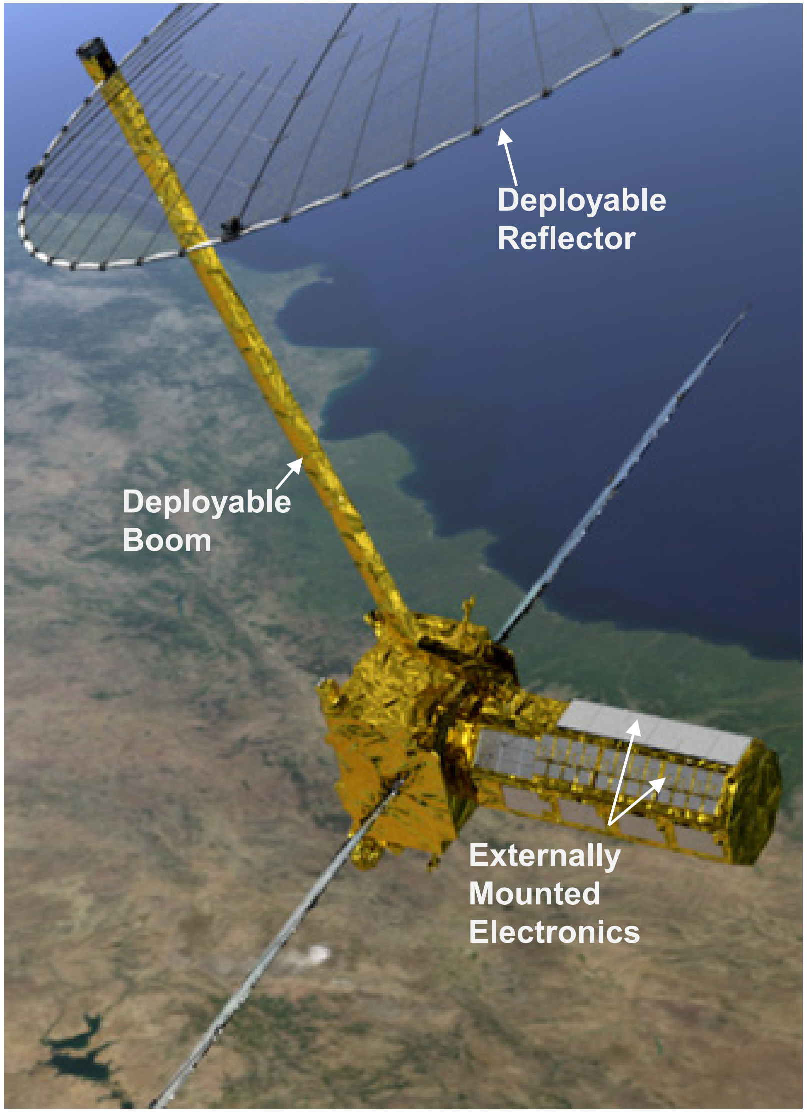
Flight EIK Thermal Pallet

Embedded CCHPs in structural plate with direct contact to instrument electronics (source) and LHP Evaporator (sink)

NASA-ISRO Synthetic Aperture Radar (NISAR)

(Courtesy of Frank Kelly, JPL NISAR Thermal Lead)

- The NISAR Mission
  - NASA-ISRO Synthetic Aperture Radar
  - NISAR will measure surface motion over span of 12 days to study:
    - Ice Sheet Collapse, Earthquakes, Volcanoes, Landslides
- Thermal Challenges
  - Thermal environment
    - To observe both North and South Poles the Instrument is required to operate both sun facing and space facing
  - Externally mounted boxes
    - Majority of the Instrument electronics are mounted to the exterior with radiators built into the high dissipation boxes
  - Deployable boom for the Radar
    - A segmented boom that deploys in orbit
    - Thermal control and analysis required for each of the five deployment phases
  - Deployable reflector
    - ASTRO Northrop Grumman supplying the deployable 12m aperture radar mounted on the deployable boom
- Thermal requirements are being met with coatings, insulation, heaters, and mechanical thermostats

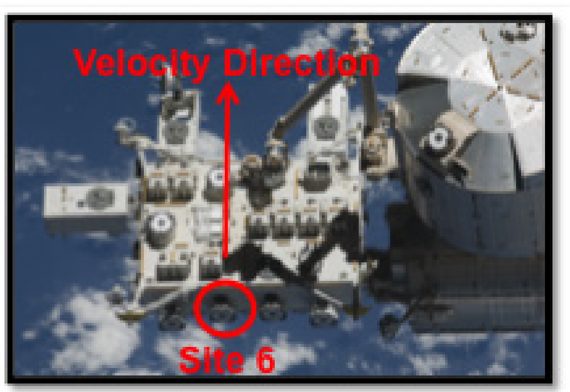


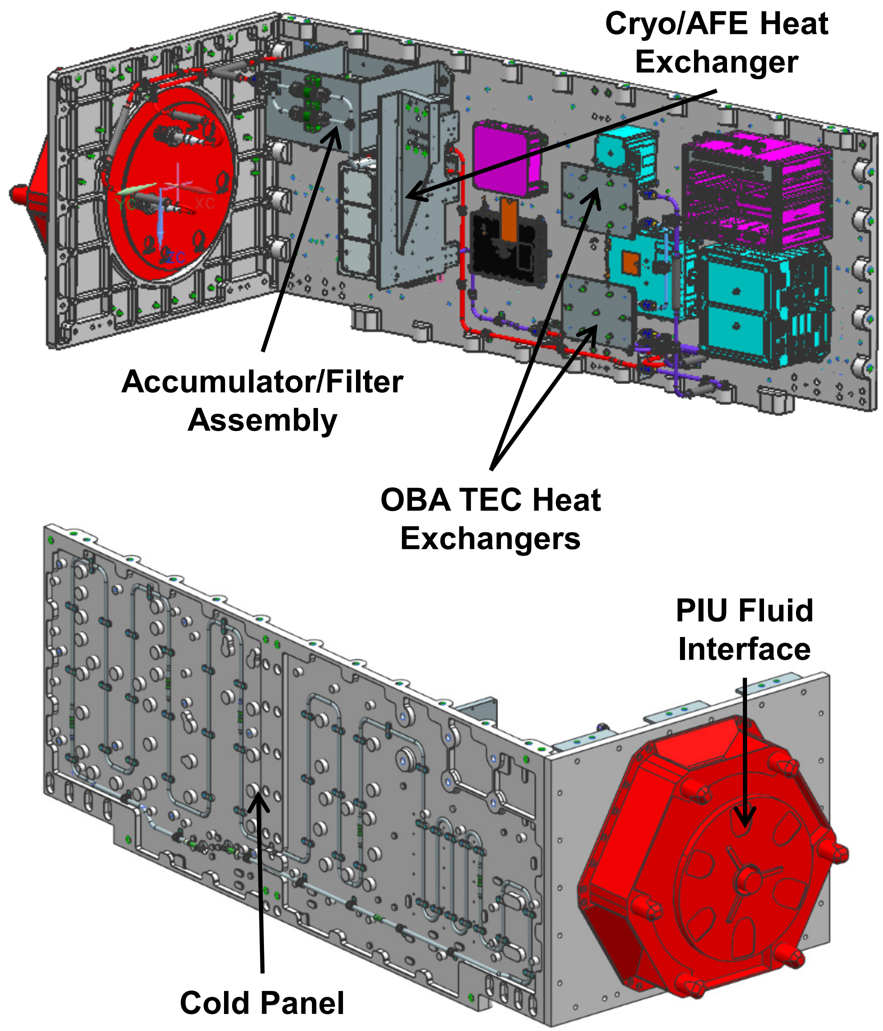
Orbiting Carbon Observatory-3

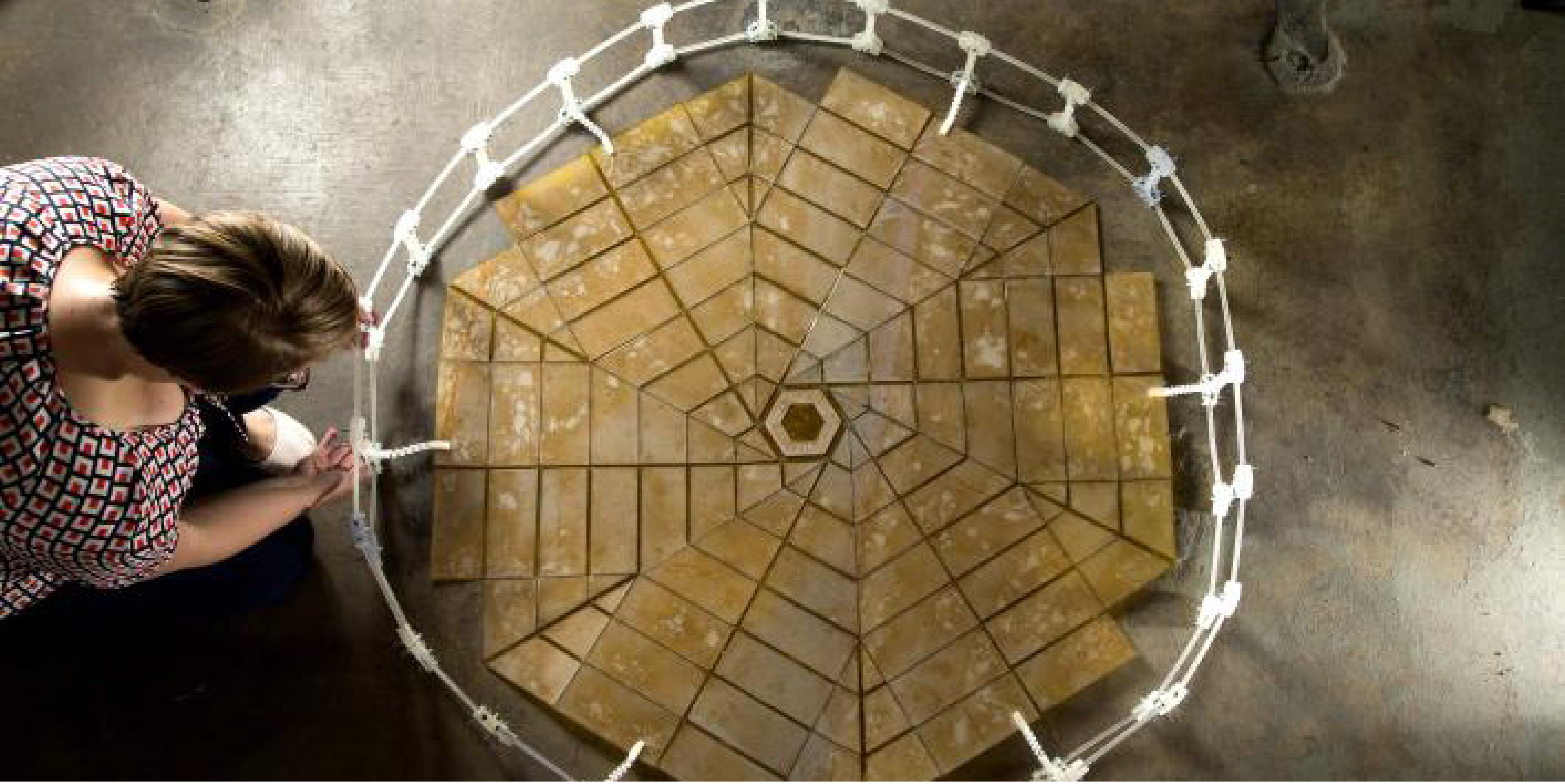
(Courtesy of Brian Carroll and Josh Kempenaar, OCO-3 Thermal Lead)

Awaiting launch in late April, 2019

- The thermal control system utilizes the JEM-EF Active Thermal Control System (pumped fluid loop)
- Four thermoelectric coolers cool the Optical Bench Assembly (OBA)
- Two cold plates remove heat from four thermoelectric coolers (2 per cold plate)
- A "Cold Panel" provides structure and heat rejection for electronics
- Accumulators and fluid filters
- Operational heaters provide thermal stability for AFE, OBA, and PMA







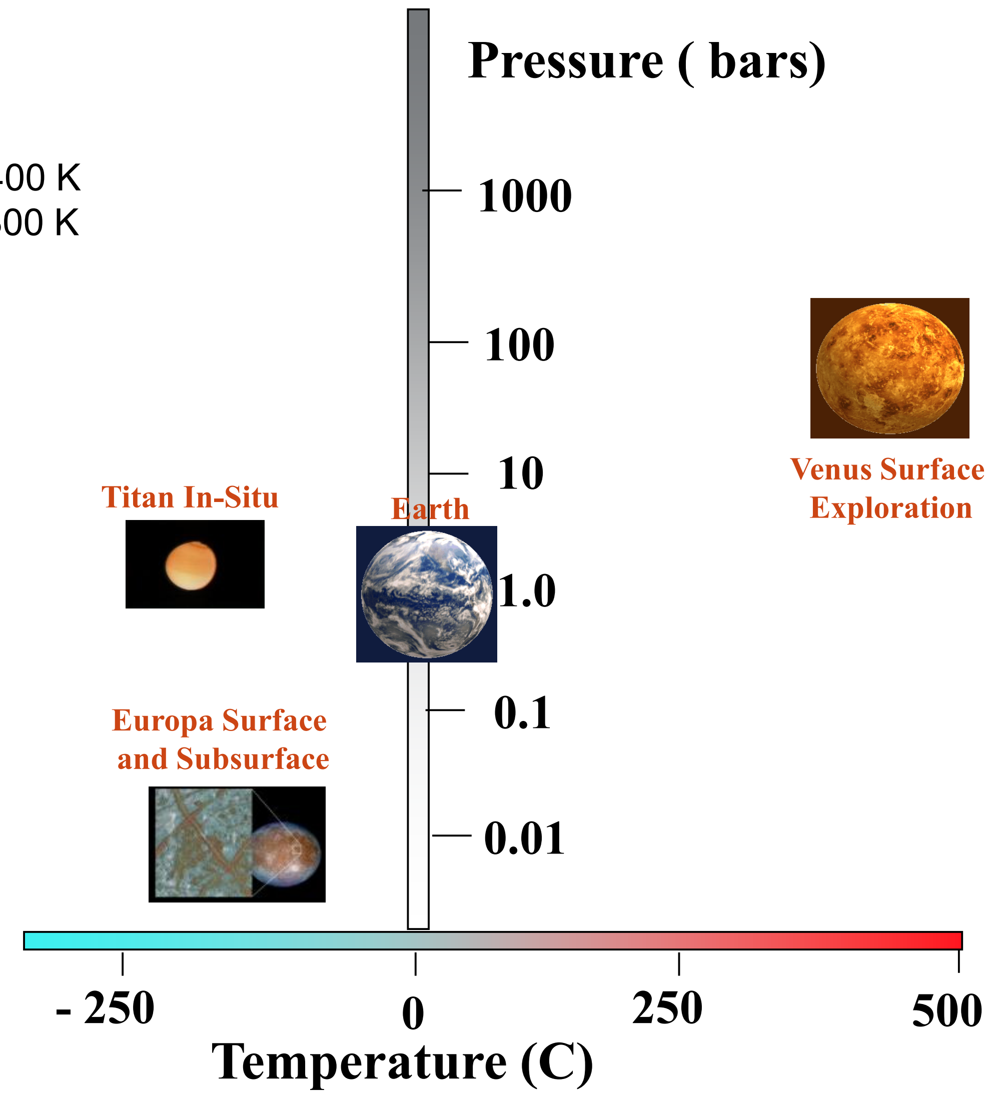
Thermal Technology Challenges

Jet Propulsion Laboratory
California Institute of Technology

TCS Challenge: Missions to Extreme Environments

Challenge: Extreme Environments

Lunar Diurnal: 100 to 400 K
Mars Diurnal: 150 to 300 K



Mission pulls on thermal technology

SMD Div.	Mission	Timeframe	Thermal Challenges	Technology Focus
Planetary Science	Ocean Worlds exploration of ice and under-ice oceans	Far-term	Extreme cold temperature and pressure; management of nuclear power source; isothermal skins	Active and passive two-phase systems
	Venus landers (long duration)	Far-term	High temp. and press. environment; mngmt of nuclear power source	Closed-cycle heat pump[1]
	Venus landers (1-2 day surf. life)	Mid-term	High temp. and press. environment	Phase change material and expendable coolant system
	Solar-powered outer planet missions	Mid-term	Waste heat reclamation over multiple interfaces and long distances	Actively pumped two-phase thermal control
	Low-power, long-duration diurnal, non-nuclear landers	Mid-term	Surviving the long night with minimal energy available for heating	High turndown heat switch; variable heat rejection radiator
	Cryogenic Sample Return	Mid-term	Maintaining sample at cryogenic temp throughout EDL	Mechanical cryocooler; expendable coolant system
Earth Science	LIDAR, InSAR	Mid-term Near-term	High heat fluxes; isothermal phase electronics; reflect array thermal stability	Single-phase (near-term) and two-phase (mid-term) pumped loops; RF transparent MLI
	Science Stations	Mid-term Far-term	Many concurrent payloads with total dissipations > 15 kW	Single-phase (near-term); Two-phase (far-term) thermal control

[1]Not included on JPL Roadmap and relies on NASA GRC Stirling-based heat pump

Cross-cutting technology pushes

Cross-cutting trends	Timeframe	Thermal Challenges	Technology Pushes
Small-Spacecraft	Near-term	Higher spacecraft heat densities requiring heat transfer across deployables	Actively pumped single-phase systems
	Mid-term	Same as above but also with higher heat fluxes and need for instrument isothermicity	Actively pumped two-phase thermal systems
Common bus for rapid development	Mid-term	Common thermal control system for both inner and outer planet missions	Actively pumped systems that provide high configurability, turndown, stability
Micro/Nano-sat swarms	Mid-term	Higher risk posture on a single flight element; thermal margin assessment	Uncertainty quantification; probabilistic design analysis
Additive Manufacturing for Heat Transfer Devices	Mid-term	How to take advantage of this flexibility in features offered by additive manufacturing	Thermal optimization design tools
Enhanced Operability	Mid-term	Surface mission operability is often limited by the thermal subsystem	More efficient heating of actuators; pseudo-real-time thermal modeling; weather-based predictive modeling

Active Two-Phase Thermal Technology Development

Eric Sunada (PI), Ben Furst (Co-I), Stefano Cappucci, Taku Daimaru,
Pradeep Bhandari, Gaj Birur, Brian Carroll, Terry Hendricks

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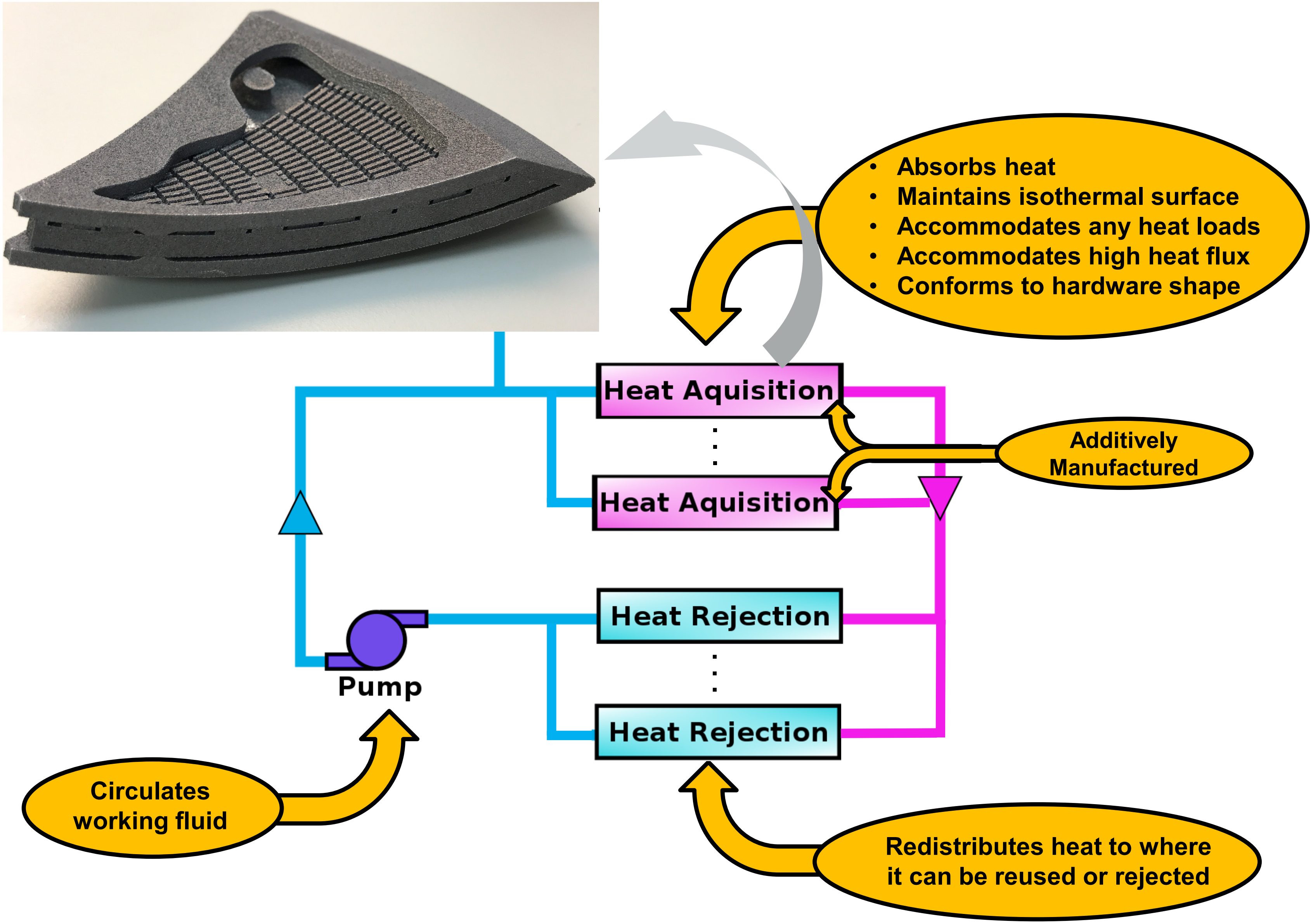
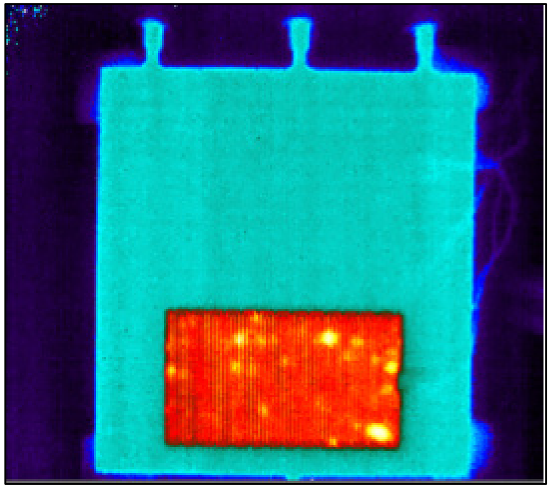
Two-Phase System Overview



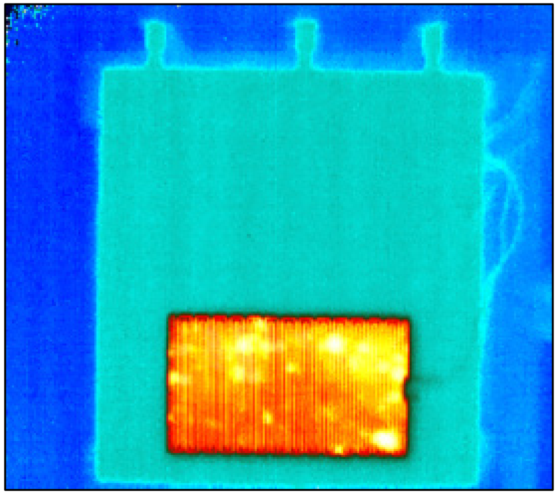
Ammonia Testbed

Evaporator IR Images

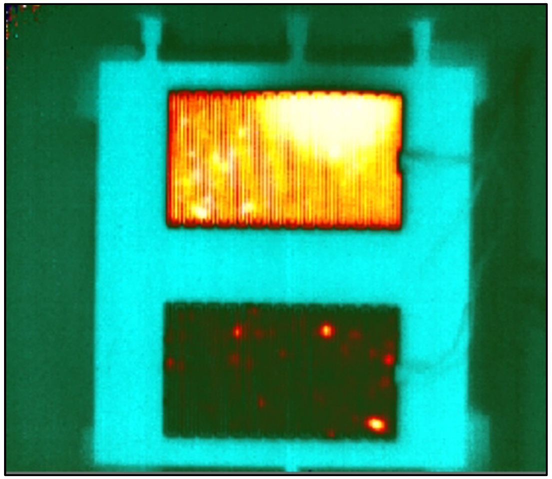
Pump Flowrate: 90 g/min
Accumulator Temperature: 26°C
Evaporator Temperature: 28°C



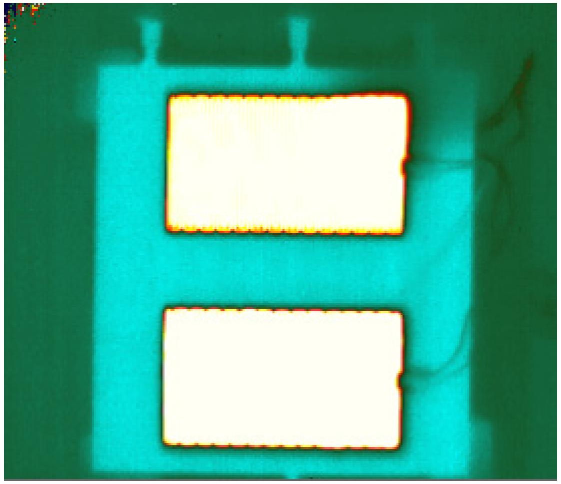
30 W



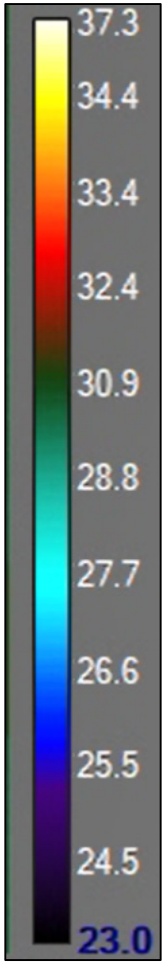
100 W



150 W
(100 W top; 50 W bottom)

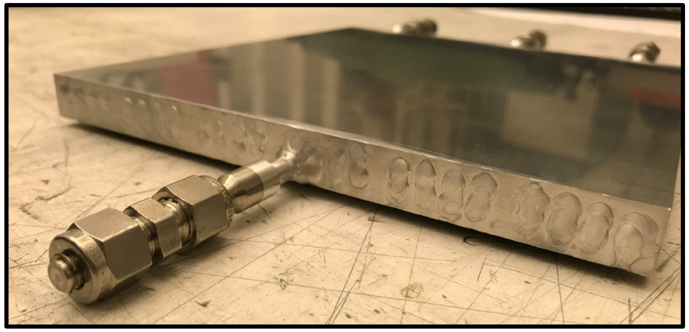


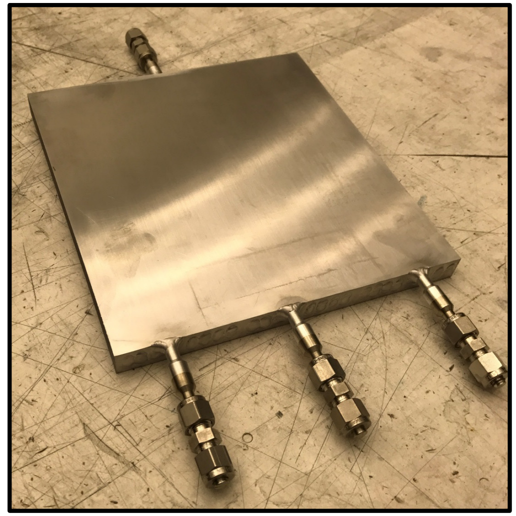
325 W
(150 W top; 175 W bottom)



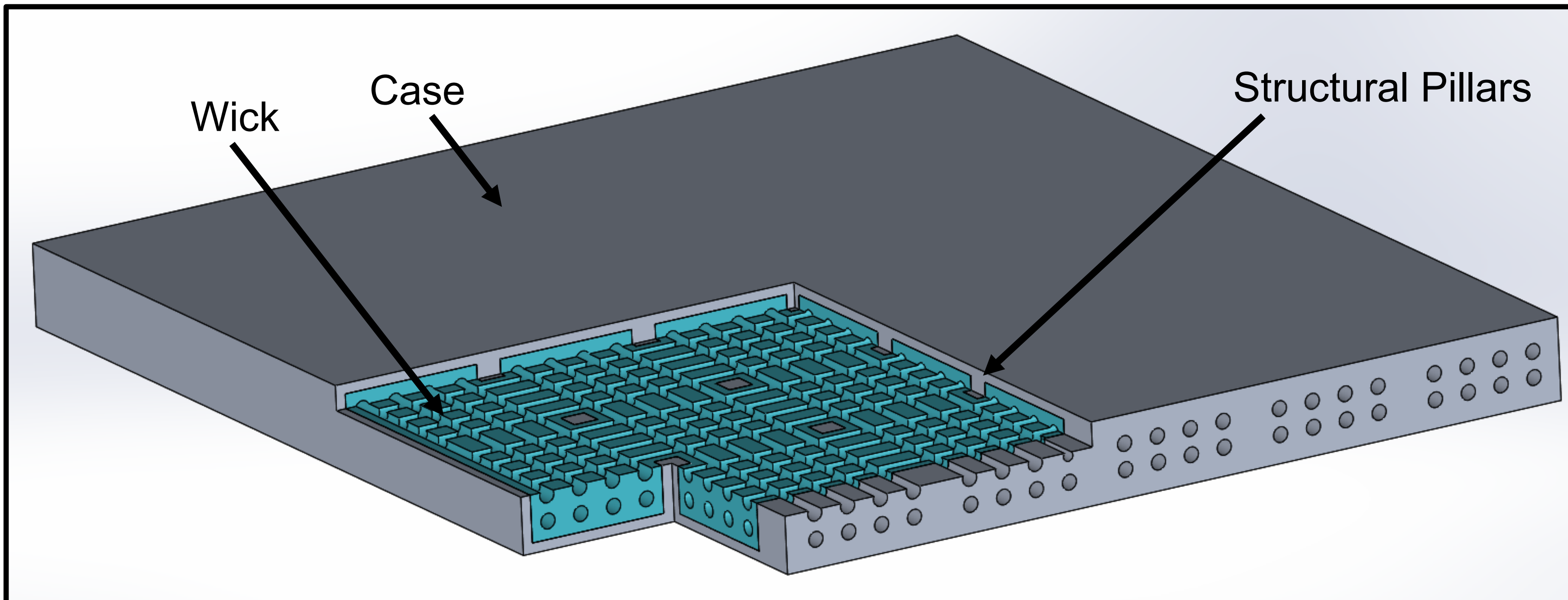
Ammonia Testbed

Evaporator Design



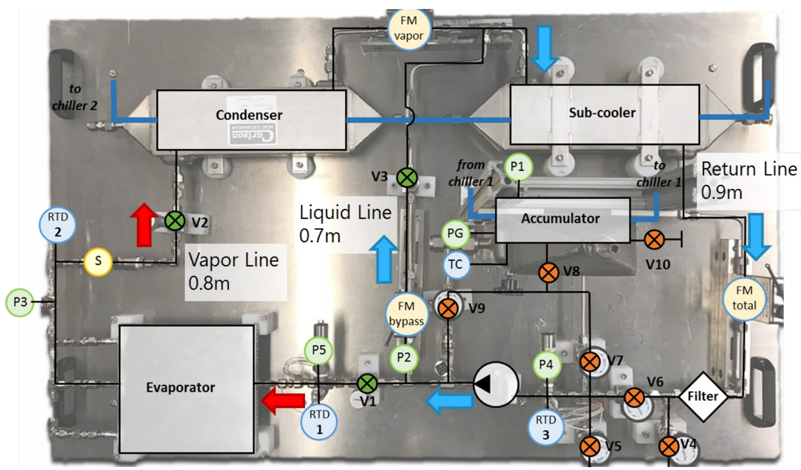


Fabrication: DMLS
Material: Aluminum
Size: 8.4” x 7.8” x 0.63”
MAWP: 200 psig
Max Pore Size: 22 µm
Permeability: 1e-13 m^2
Porosity: 24%

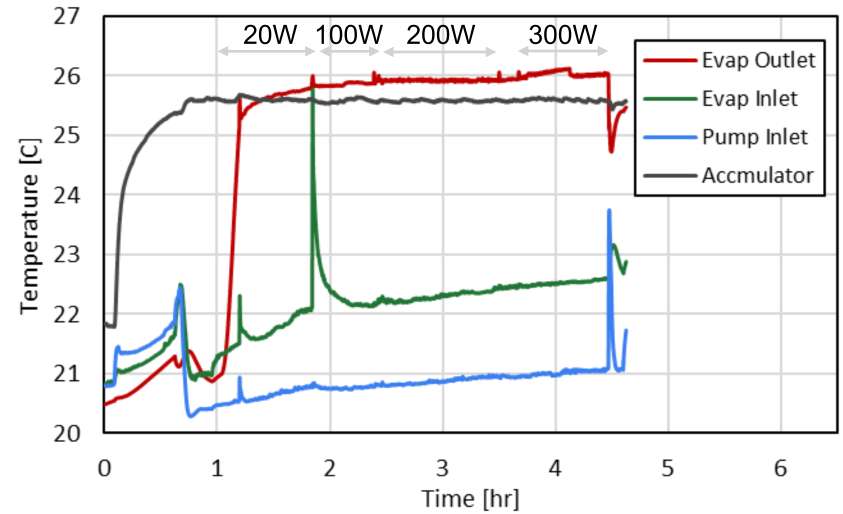


Modeling + Testing

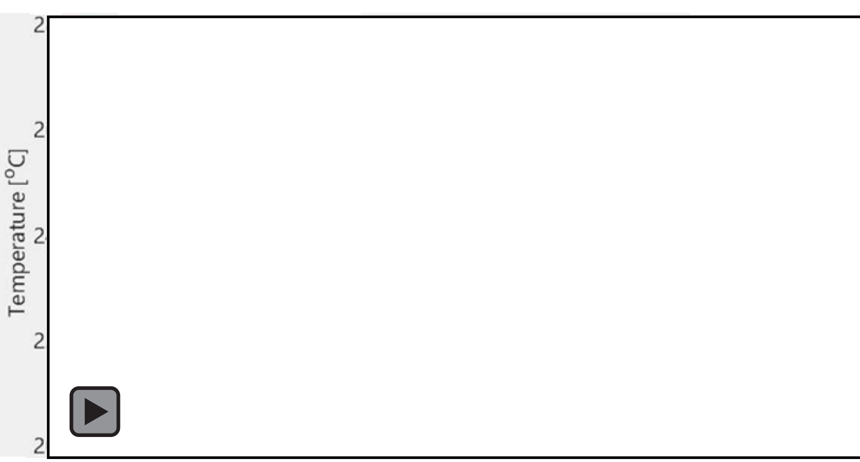
Laboratory Test Loop



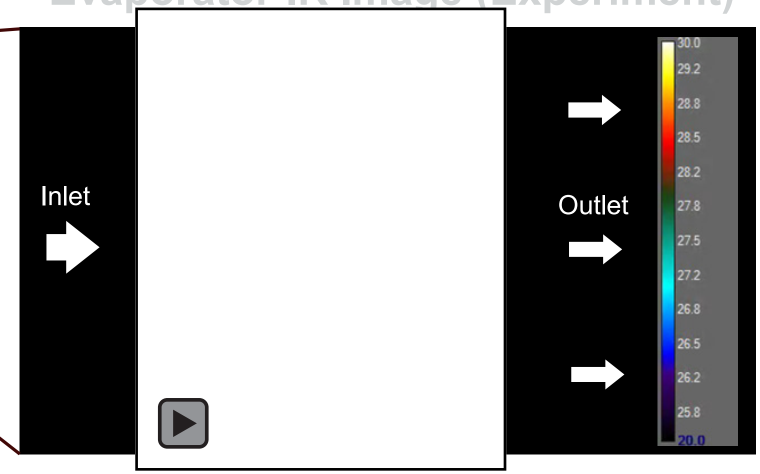
Ground Demonstration



Numerical Simulation

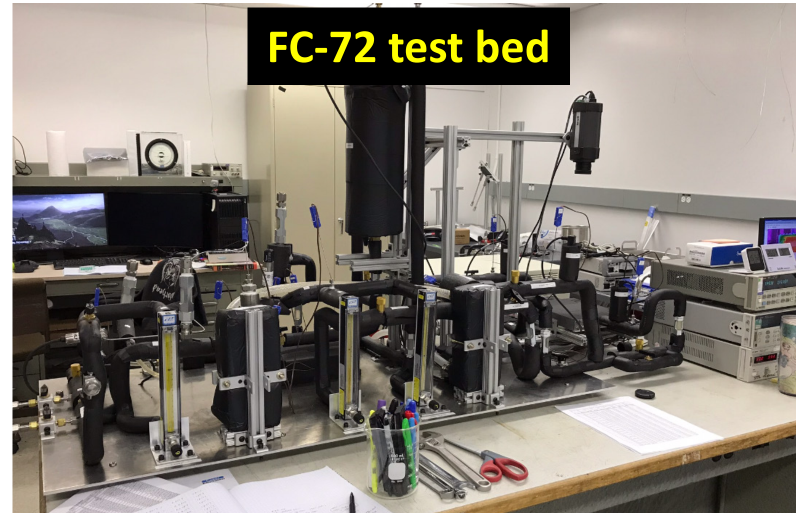


Evaporator IR Image (Experiment)

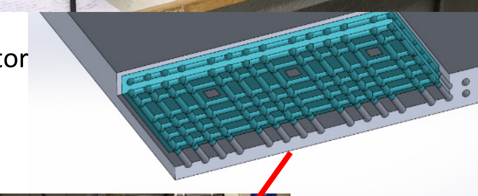


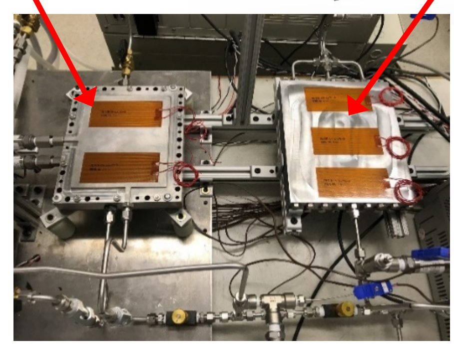
Mechanically Pumped Two-Phase Thermal Control

Two-Phase Test Beds at JPL

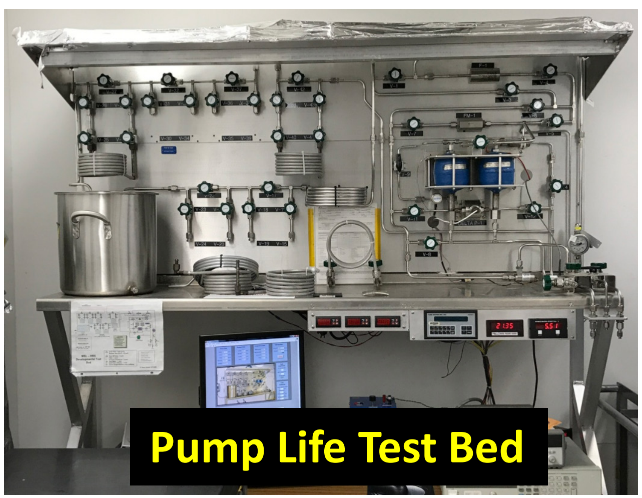


316 Stainless evaporator with 3D printed wick





3D Printed aluminum evaporator



JPL Internal Investigation—Eric Sunada/Ben Furst

NASA SBIR/STTR Technologies

S3.06-8949 - A Two-Phase Pumped Loop Evaporator with Adaptive Flow Distribution for Large Area Cooling

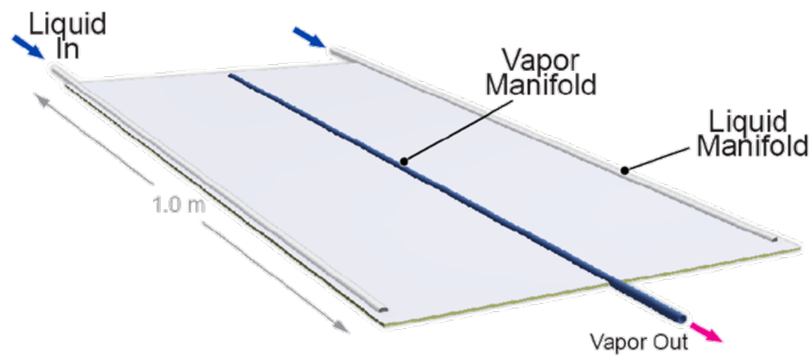
PI: Weibo Chen
Creare, LLC - Hanover, NH

Identification and Significance of Innovation

Large spacecraft need a reconfigurable thermal control system to cool multiple instruments and reject heat through multiple radiators
A microgravity-compatible evaporator having a large cooling area to maintain the temperatures of multiple electronics and instruments
--Very large cooling area to accommodate a large number of loads with different heat flux densities, power levels, sizes, and shapes
--Adaptive flow distribution ability to prevent dryout
--Unique design to provide strong structural support for covers
Benefits

--Uniform cooling temperature with spatial variation <0.2 K
--Simplify vehicle level system integration
--Reduce pumping power by reducing liquid recirculation
--Lightweight and low liquid holdup
--Microgravity compatible operation

Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)



Technical Objectives and Work Plan

Technical Objectives
Reliable fabrication and assembly processes for lightweight evaporator
High-fidelity evaporator design model
Stable and isothermal operation with highly nonuniform heat flux distribution
Gravity-insensitive operation
Phase II Work Plan
Fabrication process optimization and separate effects testing
Evaporator design analysis
Evaporator fabrication
Evaporator thermal performance testing
-- Challenging heat flux distribution and different orientations

NASA Applications

- Thermal control system for spacecraft to Saturn's moon Enceladus
- Two-phase pumped loops for future remote sensing science missions, including Surface Water and Ocean Topography (SWOT)
- Two-phase pumped loops for large spacecraft with a large number of instruments

Non-NASA Applications

- Two-phase thermal control systems in commercial and military satellites, aircraft, and vehicles
- Thermal management systems for high-power electronics systems

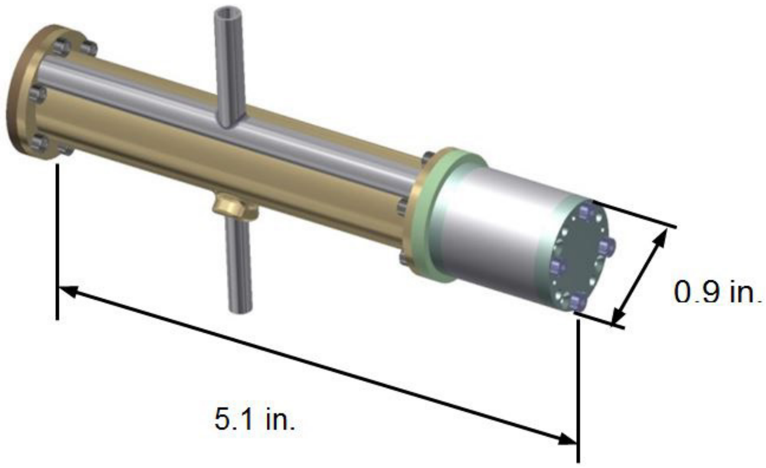
Firm Contacts

Weibo Chen
Creare, LLC
16 Great Hollow Road
Hanover, NH, 03755-3116
PHONE: (603) 643-3800
FAX: (603) 643-4657

An Efficient, Reliable, Vibration-Free Refrigerant Pump for Space Applications

SBIR Ph II—Creare LLC, PI: Dr. Weibo Chen

- Significance of the innovation
  - An innovative refrigerant pump to enable reliable refrigerant circulation in two-phase pumped loops
  - Long-life, vibration-free bearing technology for reliable operation
  - Unique pumping mechanism for low Net Positive Suction Head (NPSH), preventing cavitation in impeller and bearing liquid film
  - Efficient operation for low flow rate and high pressure rise
- Benefits
  - Compact, lightweight, and low pumping power
  - Ultra-reliable
  - No exported vibration
- Estimated TRL at beginning and end of contract: (Begin: 3 End: 4)



Pump Performance
ΔP =10 psid
$\dot{V}$ = 2 cc/s
$W_{electrical}$ = 1.6 W
M = 198 g
Speed: 12,000 rpm
NPSH: 0.2 psi

Passive Two-Phase Thermal Technology Development

Ben Furst, Vapor Chamber PI

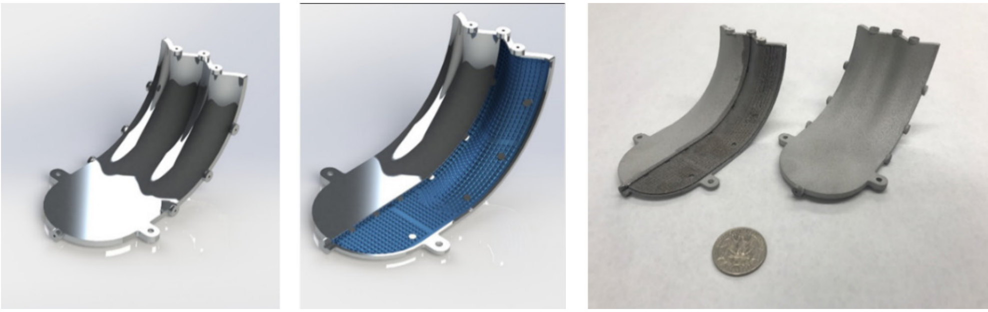
Takuro Daimaru, Oscillating Heat Pipe PI

Jet Propulsion Laboratory
California Institute of Technology

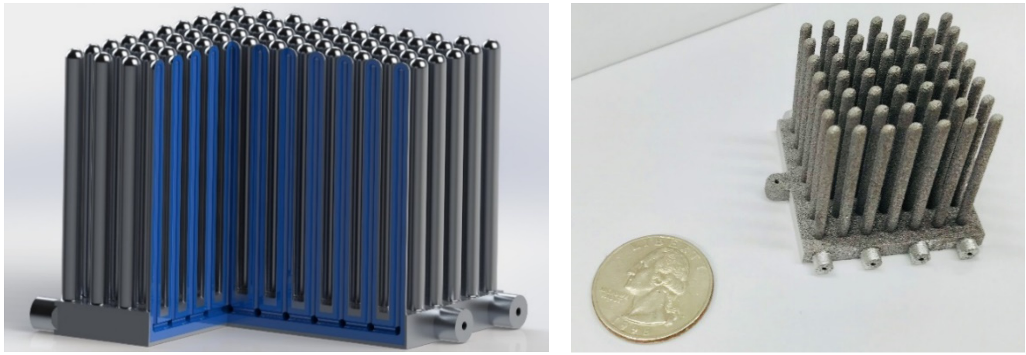
Passive Two-Phase Thermal Control

Vapor Chamber Development

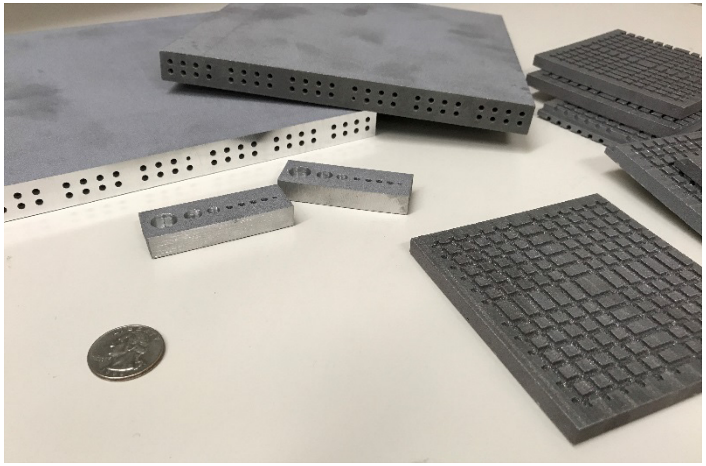
- 3D printed two-phase vapor chambers capable of conformal shapes



Additively manufactured vapor chamber with complex 3D geometry (left/center shows the CAD, right shows the fabricated part). This unit was designed at JPL. It is currently undergoing testing



An additively manufactured heat sink with integrated heat pipes and vapor chamber. The cutaway (right) shows the integrated wicking structure (blue) and channels for vapor flow of the heat pipes/vapor chamber.

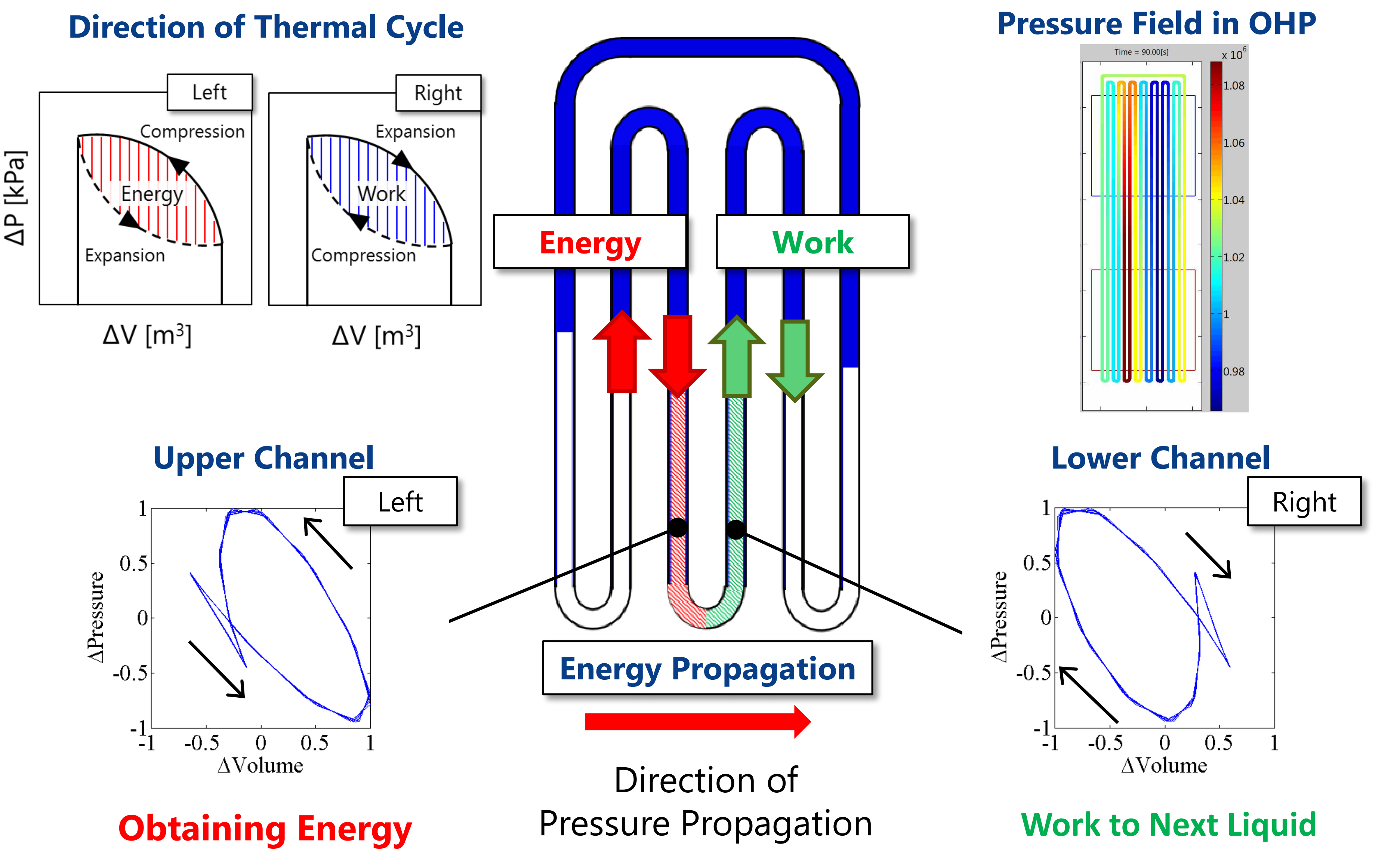


Several additively manufactured units with integral wick structure. The wicking properties of these coupons were well characterized under the current project.

JPL Internal Investigation—Ben Furst, PI

Passive Two-Phase Thermal Control

Research in Oscillating Heat Pipe Phenomena



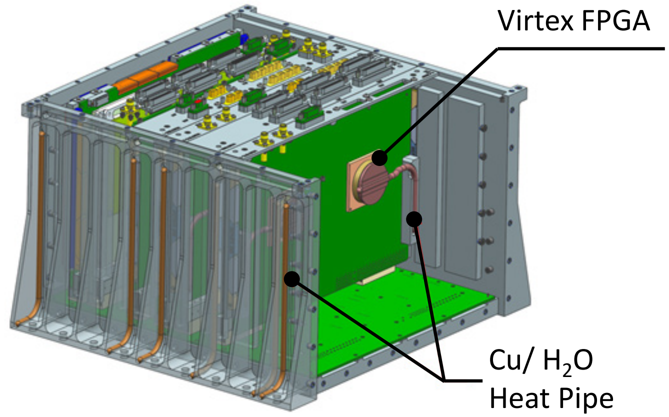
JPL Internal Investigation—PI, Takuro Daimaru

Passive Two-Phase Thermal Control

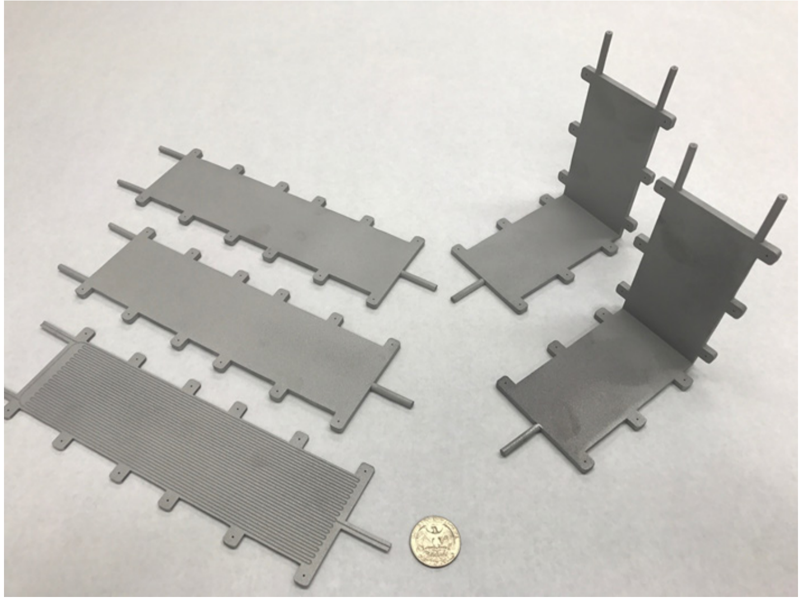
Oscillating Heat Pipe Application Prototyping

Multi-Functional OHP System

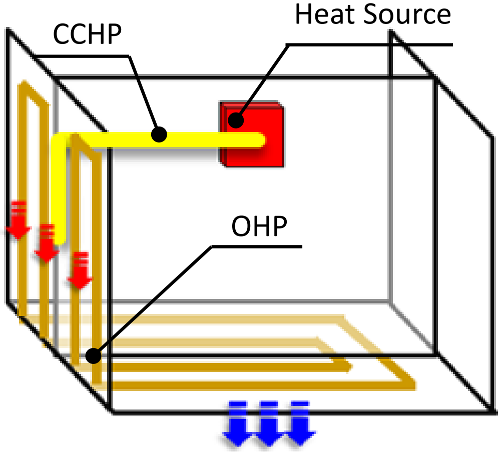
- 3D printed OHPs
- Integrated thermal-structural chassis with 2D heat transfer
- Capable of handling fluxes of 100's W/cm^2 due to evaporation and forced convection



Current electronic chassis TCS uses Cu/H2O CCHPs



3D Printed aluminum OHPs



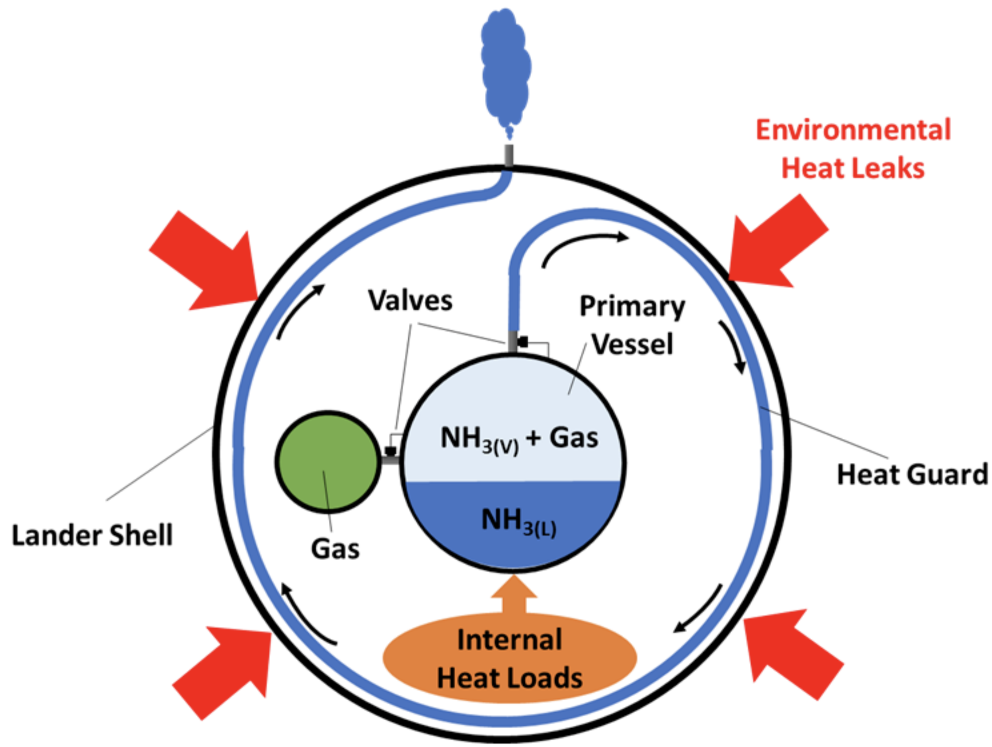
OHPs integrated directly in the structure permit more efficient heat transfer

JPL Internal Investigation—PI, Takuro Daimaru

Expendable Coolant Systems

SBIR Phase I Z2.01-8692: Consumable Based Cooling For Venus Landers
PI: Calin Tarau , Advanced Cooling Technologies, Inc. - Lancaster, PA

- To extend the survival duration of a Venus lander environment (460°C, 92 bar) to at least 24 hours, ACT has demonstrated an ammonia/compressed gas system that has the potential for significant mass savings over the state-of-the-art
- Developed a mathematical model for consumable-based cooling system, which was validated with experiments
- Developed a sub-scale prototype and tested its performance with three pairs of consumable fluid (water/argon, water/helium and ammonia/helium)



Single-Phase Pumped Fluid Loop Developments

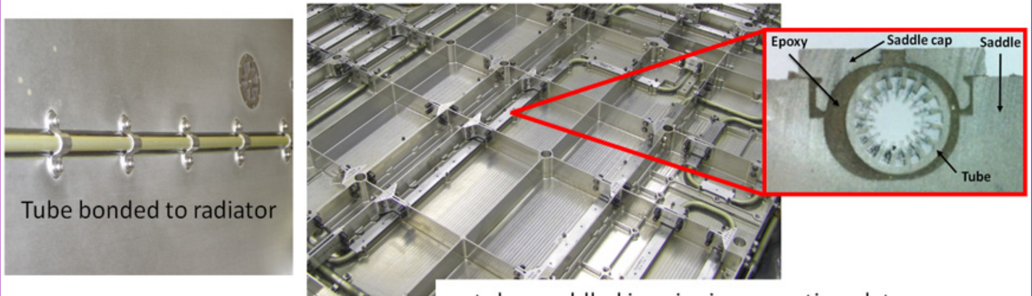
A.J. Mastropietro

Jet Propulsion Laboratory
California Institute of Technology

SBIR Phase 2 with Sheridan Solutions and Fabrisonic LLC – “Ultrasonic Additive Manufacturing for Capillary Heat Transfer Devices and Integrated Heat Exchangers” / Period of Performance Ended April 2018

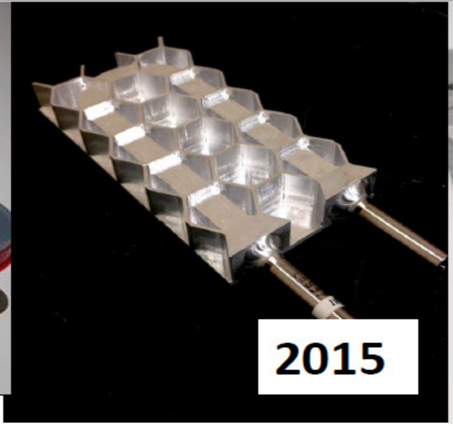
Novel additive manufacturing technique for fabricating large aluminum liquid cold plate heat exchangers to support more cost effective and efficient Mechanical Pumped Fluid Loop Thermal Architectures for future flagship and manned missions. The technique uses subtractive manufacturing to create coolant channels in a virgin slab of aluminum and then additively consolidates an aluminum roof over the channels thereby reducing part count, complexity, and mass.

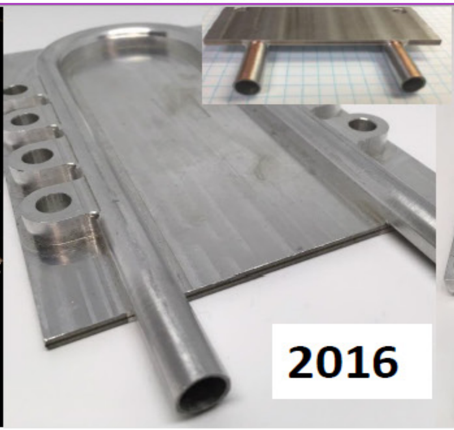
Current State of the Art for HRS Heat Exchanger Fabrication

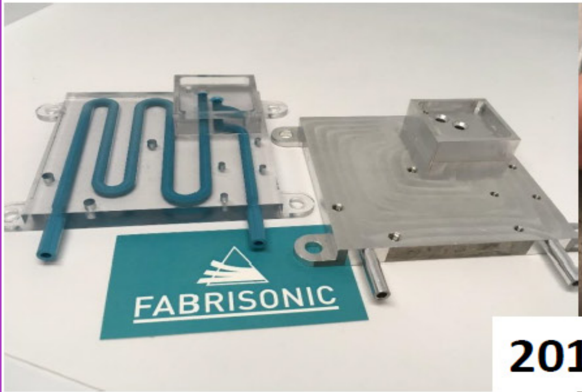


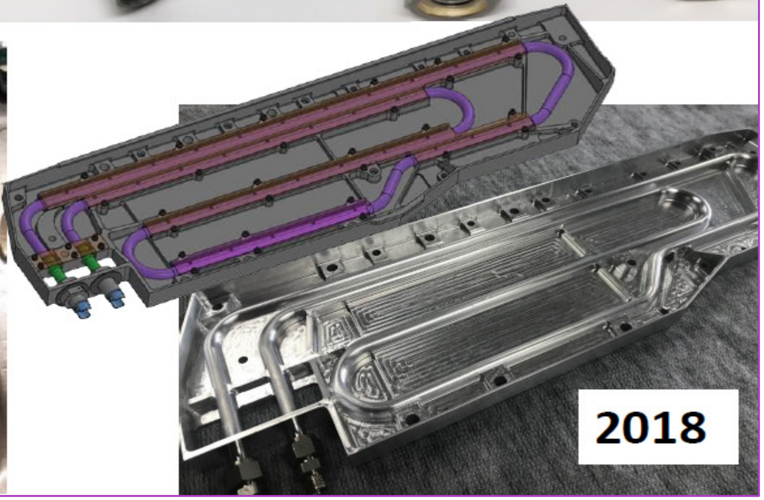
or tubes saddled in avionics mounting plate

UAM prototypes in different phases of testing and machining



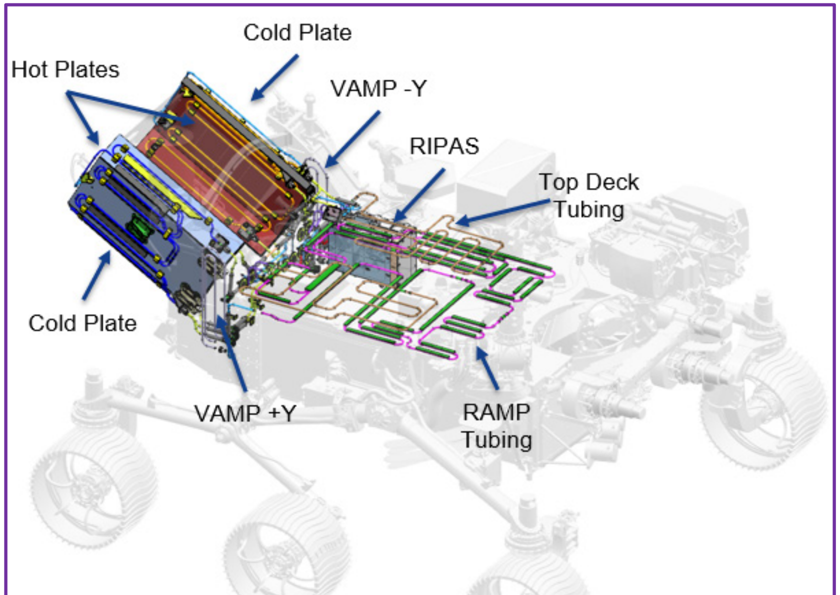




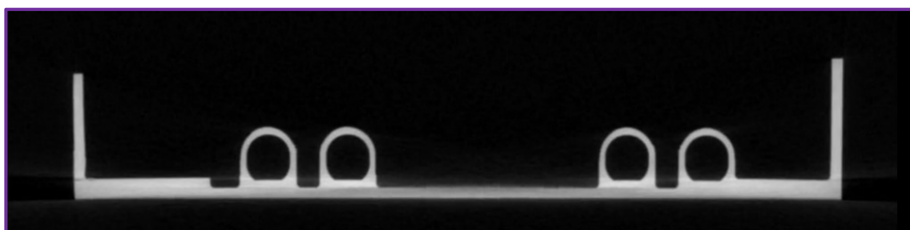


SBIR Phase 2 with Sheridan Solutions and Fabrisonic LLC – “Ultrasonic Additive Manufacturing for Capillary Heat Transfer Devices and Integrated Heat Exchangers” / Period of Performance Ended April 2018

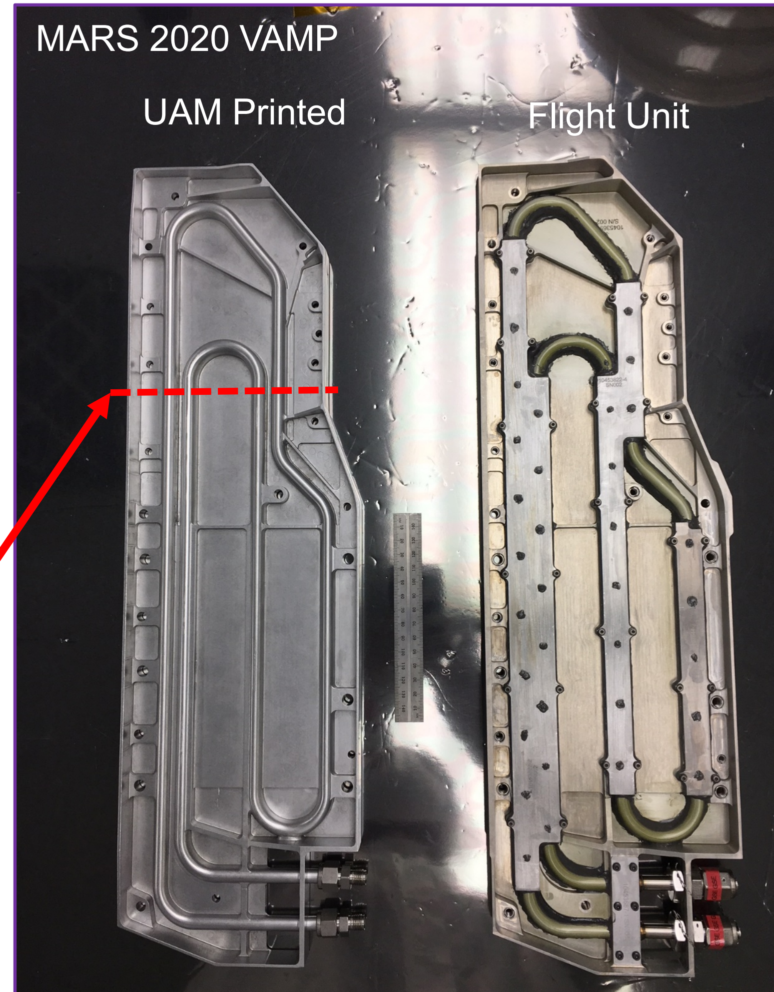
Final Deliverable M2020 Rover Vertical Avionics Mounting Plate (VAMP) ↓



http://fabrisonic.com/3dprinting/wp-content/uploads/2018/05/NASA-HX-Case-Study.pdf



↑ CT Scan shows excellent consolidation



↑ UAM part had 30% less mass compared to flight unit

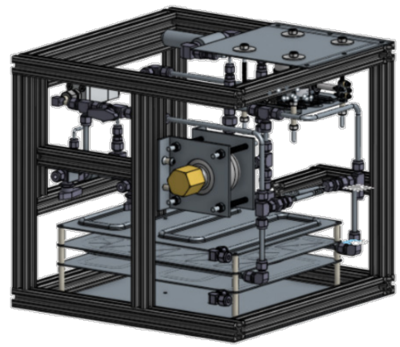
CubeSat Technology Gaps Identified

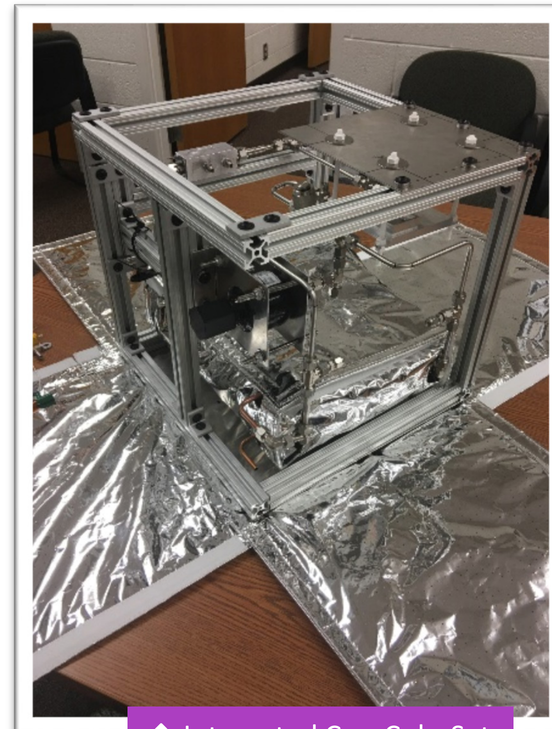
- The increasing power density of CubeStats and environmental load variation associated with interplanetary missions poses thermal control challenges
- Need for inexpensive and miniaturized
  – Deployable radiator systems
  – Radiator turndown systems
  – High conductance chassis

Active CryoCubeSat (mini pump fluid loop and 3d printed heat exchangers)
Small Spacecraft Technology Partnership between NASA JPL and USU
Period of Performance ended 2018

- Development of a 6U miniaturized active thermal control system for CubeSats to provide cryogenic cooling for IR detectors in the 75-100K range
- Completed 17 steady state cases to fully characterize the Mini MPFL/Cryocooler System and simulated 12 orbits to determine transient response of system
- System can manage **114W continuously** while maintaining a cold finger temp at 82K with 0.25W lift with a heat rejection temperature (HXer interface) maintained <60°C.
- With about a 20°C swing on the HXer, cold finger could be maintained at 90K with 0.5K/hr stability

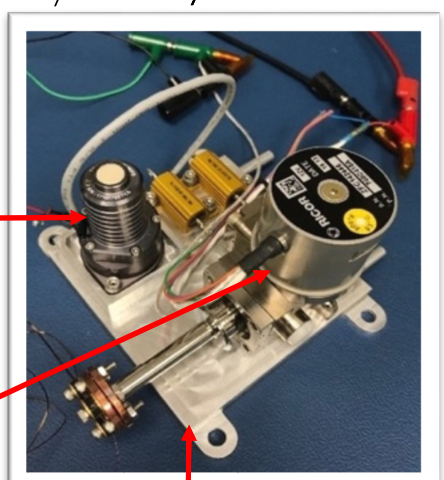
Final Testing September 2018 ↓





↑ Integrated CryoCubeSat

Ultrasonic Additively Manufactured Radiator (2Ux3U)



TCS M510 MicroPump

Ricor K508N Tactical Cryocooler

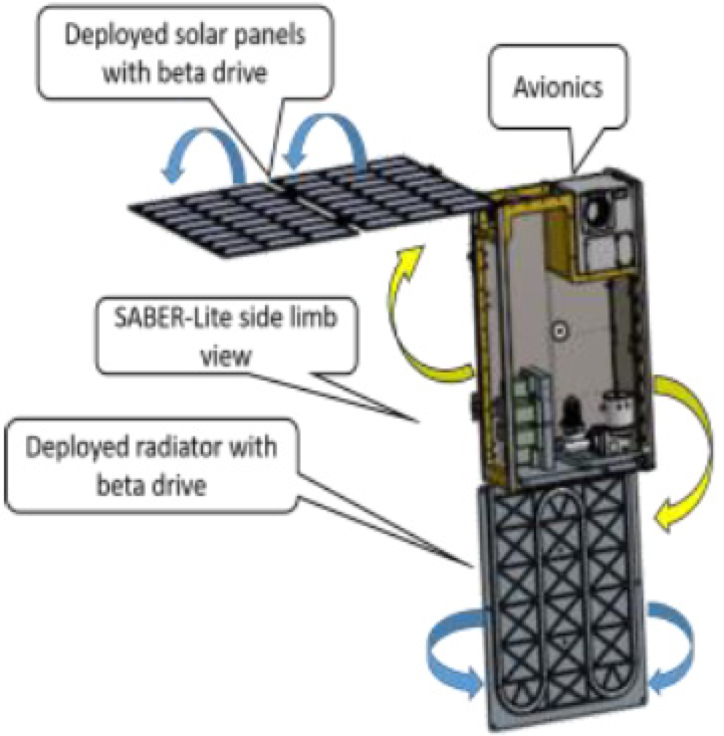
Ultrasonic Additively Manufactured Heat Exchanger (1Ux1U)

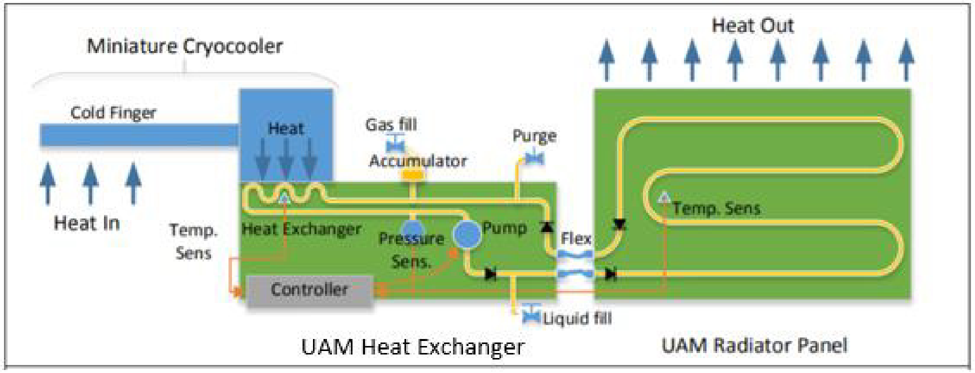
Applications: Pumped Loops for Nano- and Micro-Spacecraft

Nano- and Micro-Satellite Thermal Management Systems

- Higher heat densities associated with spacecraft miniaturization are being addressed through single-phase pumped fluid loops
- Efficient heat transfer across deployables
- Leveraging additive mfg for increased efficiency in performance, cost, and schedule

Ultrasonic Additively Manufactured Radiator (2Ux3U)





NASA Small Spacecraft Technology Program SmallSat Technology Partnerships
Section Contacts: AJ Mastropietro, Elham Maghsoudi, Stefano Cappucci

Cryogenics Systems Engineering

Jose I. Rodriguez

Jet Propulsion Laboratory
California Institute of Technology

Cryogenics Systems Engineering Group

(Courtesy of Jose Rodriguez, JPL Cryogenic Systems Engineering Group Supervisor)

Engineering & Research Capabilities

Microcoolers for space and Mars landed missions. Challenge: Low Power Efficiency, High Cost and Poor Reliability. POC: Drs. Jose I. Rodriguez, Dean Johnson, Ian McKinley

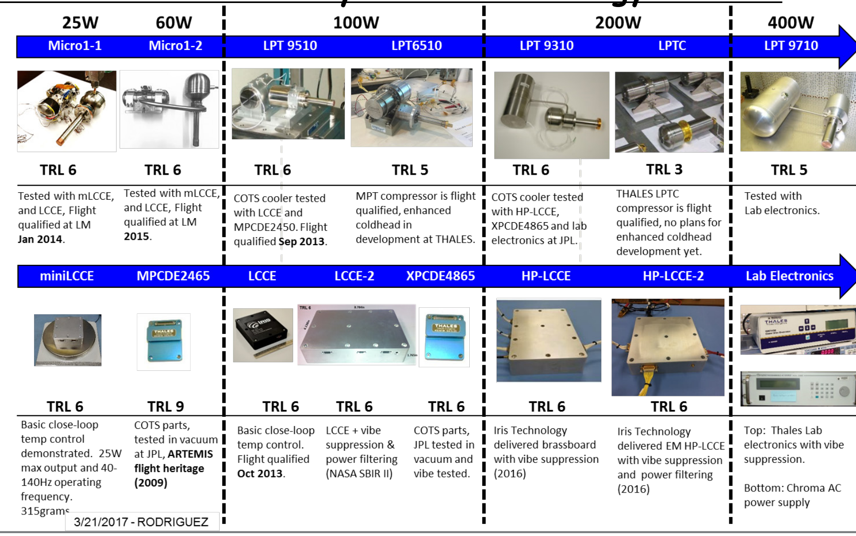
Architecting multi-stage passive cooling systems for LEO and outer planetary missions. Challenge: Solar Power Missions with Large Solar Arrays, Extreme Environments, Materials, Reliability and High Cost. POC: Dr. Jose I. Rodriguez, Doug Bolton, Perry Ramsey

Pulse tube cryocooler technology advancements for cooling to 40K. Challenge: Complex Pulse Tube Designs, Thermodynamic Modelling, CFD Analysis, Materials. POC: Dr. Dean Johnson

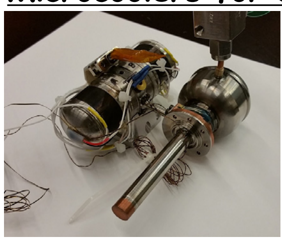
Cryogenic technology development and infusion on future remote sensing science instruments. Challenge: High Development Costs, TRL6 High Qualification Costs, Materials and Reliability. POC: Drs. Jose I. Rodriguez, Perry Ramsey, Ian McKinley

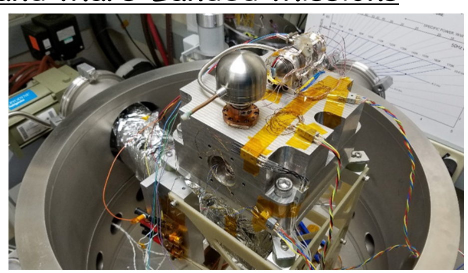
Flight qualification and characterization testing of cryocooler systems for space flight instruments. Challenge: High Cost and Maintenance of Special Test Equipment and Flight Certified Facilities. POC: Dr. Dean Johnson

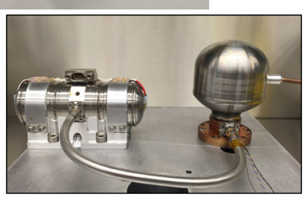
Low Cost Pulse Tube Cryocooler Technology- Status

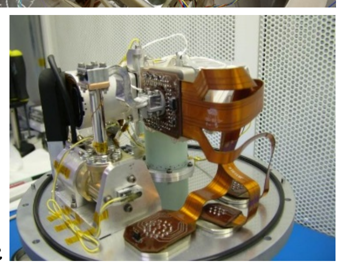


Microcoolers for Space and Mars Landed Missions



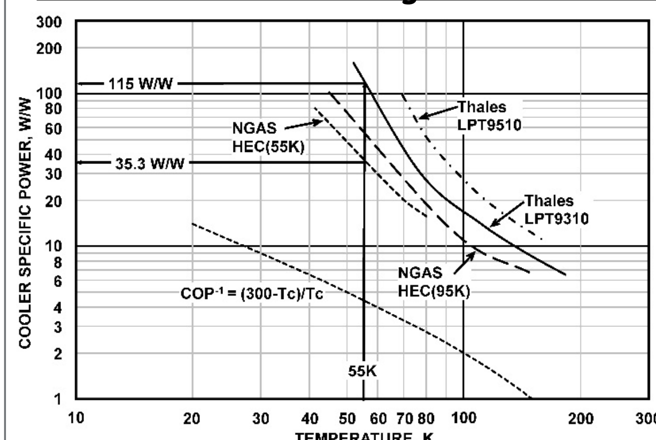


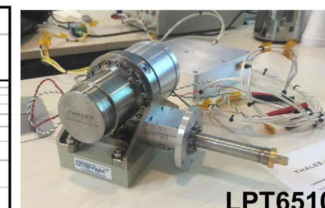


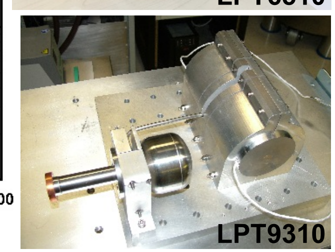


Small form factor and less than 500g microcoolers enable efficient cryogenic cooling for CubeSats and compact science instruments

Characterization Testing of Cooler technologies







Targeting strategic improvements to increase thermodynamic efficiency

Cryogenics Systems Engineering Group

Long-life Space Cryocooler Operating Experience

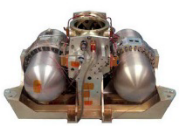
Recent NGAS
Himawari-9 (2 units) Nov 2016
GOES-R (2 units) Nov 2016
GOES-S (2 units) Mar 2018

> 15 yrs → AIRS
> 13 yrs → TES
TES powered off 1/31/2018
> 3 yrs → OCO-2

Cooler / Mission	Hours/Unit	Comments
Air Liquide Turbo Brayton (ISS MELFI 190K)	85,600	Turn on 7/06, Ongoing, No degradation
Ball Aerospace Stirling		
HIRDLS (60K 1-stage Stirling)	83,800	8/04 thru 3/14, Instr. failed 2008; Data turned off 3/14
TIRS cooler (35K two-stage Stirling)	27,900	Turn on 3/6/13, Ongoing, No degradation
Creare Turbo Brayton (77K NICMOS)	57,000	3/02 thru 10/09, Off, Coupling to Load failed
Fujitsu Stirling (ASTER 80K TIR system)	141,700	Turn on 3/00, Ongoing, No degradation
JPL Sorption (PLANCK 18K JT (Prime & Bkup))	27,500	FM1 (8/10-10/13 EOM); FM2 failed at 10,500 h
Mitsubishi Stirling (ASTER 77K SWIR system)	137,500	Turn on 3/00, Ongoing, Load off at 71,000 h
NGAS (TRW) Coolers		
CX (150K Mini PT (2 units))	161,600	Turn on 2/98, Ongoing, No degradation
HTSSE-2 (80K mini Stirling)	24,000	3/99 thru 3/02, Mission End, No degrad.
MTI (60K 6020 10cc PT)	141,600	Turn on 3/00, Ongoing, No degradation
Hyperion (110K Mini PT)	133,600	Turn on 12/00, Ongoing, No degradation
SABER on TIMED (75K Mini PT)	129,600	Turn on 1/02, Ongoing, No degradation
AIRS (55K 10cc PT (2 units))	121,600	Turn on 6/02, Ongoing, No degradation
TES (60K 10cc PT (2 units))	102,600	Turn on 8/04, Ongoing, No degradation
JAMI (65K HEC PT (2 units))	91,000	4/05 to 12/15, Mission End, No degrad.
GOSAT/IBUKI (60K HEC PT)	63,300	Turn on 2/09, Ongoing, No degradation
STSS (Mini PT (4 units))	52,800	Turn on 4/10, Ongoing, No degradation
OCO-2 (HEC PT)	14,900	Turn on 8/14, Ongoing, No degradation
Himawari-8 (65K HEC PT (2 units))	12,800	Turn on 12/14, Ongoing, No degradation
Oxford/BAe/MMS/Astrium/Airbus Stirling		
ISAMS (80 K Oxford/RAL)	15,800	10/91 thru 7/92, Instrument failed
HTSSE-2 (80K BAe)	24,000	3/99 thru 3/02, Mission End, No degrad.
MOPITT (50-80K BAe (2 units))	138,600	Turn on 3/00, lost one disp. at 10,300 h
ODIN (50-80K Astrium (1 unit))	132,600	Turn on 3/01, Ongoing, No degradation
AATSR on ERS-1 (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No Degrad, Satellite failed
MIPAS on ERS-1 (50-80K Astrium (2 units))	88,200	3/02 to 4/12, No Degrad, Satellite failed
INTEGRAL (50-80K Astrium (4 units))	118,700	Turn on 10/02, Ongoing, No degradation
Helios 2A (50-80K Astrium (2 units))	96,600	Turn on 4/05, Ongoing, No degradation
Helios 2B (50-80K Astrium (2 units))	58,800	Turn on 4/10, Ongoing, No degradation
SLSTR (50-80K Airbus (2 units))	1,400	Turn on 3/16, Ongoing, No degradation
Planck (4K JT using 2 Astrium Comp.)	38,500	5/09 thru 10/13, Mission End, No Degrad.
Raytheon ISSC Stirling (STSS (2 units))	52,800	Turn on 4/10, Ongoing, No degradation
Rutherford Appleton Lab (RAL)		
ATSR 1 on ERS-1 (80K Integral Stirling)	75,300	7/91 thru 3/00, Satellite failed
ATSR 2 on ERS-2 (80K Integral Stirling)	112,000	4/95 thru 2/08, Instrument failed
Sumitomo Stirling Coolers		
Suzaku (100K 1-stg)	59,300	7/05 thru 4/12, Mission End, No degradation
Akari (20K 2-stg (2 units))	39,000	2/06 to 11/11 EOM, 1 Degr., 2nd failed at 13 kh
Kaguya GRS (70K 1-stg)	14,600	10/07 thru 6/09, Mission End, No degradation
JEM/SMILES on ISS (4.5K JT)	4,500	Turn on 10/09, Could not restart at 4,500 h
Sunpower Stirling		
RHESSI (75K Cryotel)	124,600	Turn on 2/02, Ongoing, Modest degradation
CHIRP (CryoTel CT-F)	19,700	9/11 to 12/13, Mission End, No degradation

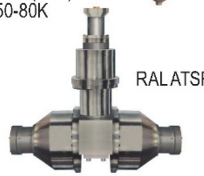

Creare NICMOS


NGAS (TRW) Mini PT


NGAS (TRW) AIRS PT


NGAS (TRW) HEC PT


Astrium (BAe) 50-80K


RAL ATSR

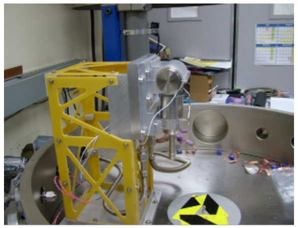

Sunpower RHESSI

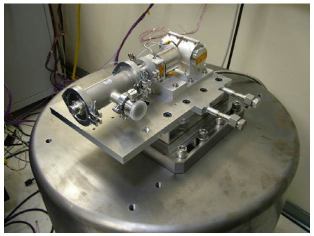
Ross 05/18/16

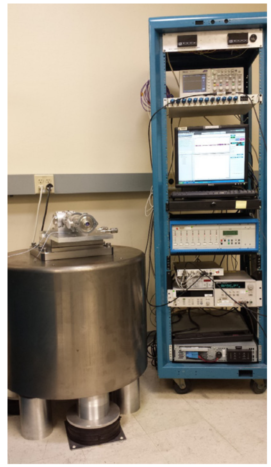
Cryogenics Systems Engineering Group

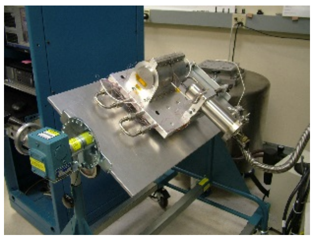
(Courtesy of Jose Rodriguez, JPL Cryogenic Systems Engineering Group Supervisor)

Cryocooler Performance Characterization Testing



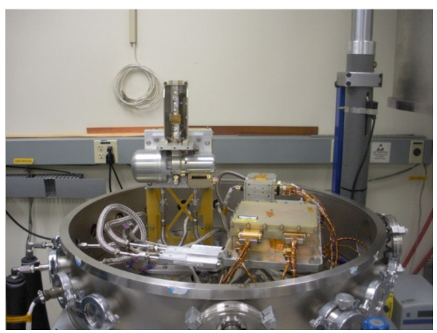






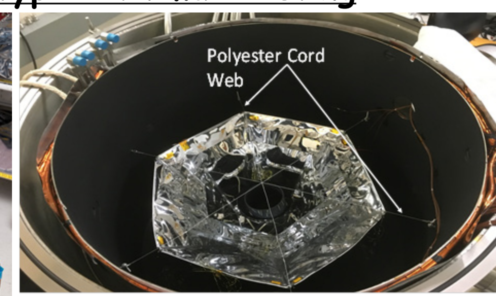
MISE Cryocooler Life-Test Laboratory

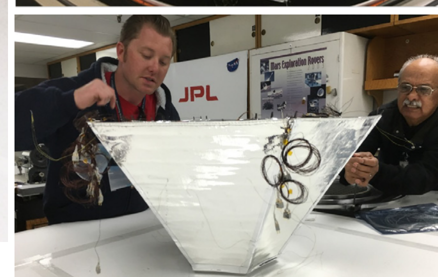
Flight Cryocooler Testing Lab



Orbiting Carbon Observatory-2 (OCO-2): Mission will collect precise global measurements of carbon dioxide (CO_2) in the Earth's atmosphere utilizing a single instrument with 3 high-resolution, grating spectrometers (0.765 μm O_2 A-band, 1.61 μm "weak" CO_2 band, and 2.06 μm "strong" CO_2 band). Single-stage High Efficiency Cooler (HEC) cools all three focal planes to 120K. Variable conductance heat pipes are used to transport the cooler waste heat to the outboard radiators.

SPHEREx 1/4 Scale Prototype Thermal Testing





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